VOLUME 1

# Geology of India

M. Ramakrishnan
R. Vaidyanadhan

India & Sri Lanka as viewed by IRS-1D WiFS

AFGHANISTAN
0
300km
SCALE
CHINA
PAKISTAN
NEPAL
BHUTAN
BANGLADESH
MYANMAR
ARABIAN SEA
BAY OF BENGAL
INDIAN OCEAN

GEOLOGICAL SOCIETY OF INDIA
BANGALORE
2010

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# GEOLOGY
# OF
# INDIA

## Volume 1

**M. RAMAKRISHNAN**
**and**
**R. VAIDYANADHAN**

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# Foreword

A phenomenal growth has been achieved in our understanding of the Geology of India since India's Independence through the efforts of the Geological Survey of India and several other State Surveys, exploration agencies, research organizations, universities, institutes and scientific societies. Many of our earlier concepts of geology in relation to structure and tectonics, stratigraphy and sedimentation, magmatism and metamorphism, and metallogeny and mineral deposits have undergone drastic changes with larger inflow of data, synchronising with the evolving global concepts of earth processes. New dimensions have been added to Indian stratigraphy by detailed geological mapping on the one hand and through geochronology and to a limited extent geophysics and geochemistry. The need for a comprehensive, nevertheless succinct account of the geology of India, keeping in view the above developments, has been keenly felt and a positive step has been taken by the Geological Society of India in entrusting to two of our outstanding earth scientists, Prof. R. Vaidyanadhan and Dr. M. Ramakrishnan, the task of addressing this need. Professor Vaidyanadhan hails from an educational stream from the Andhra University and is widely known for his expertise in geomorphology and a capability for incisive synthesis and review. Dr. M. Ramakrishnan has several decades of dedicated field work in different parts of the country to his credit under the banner of the Geological Survey of India and in guiding streams of younger scientists in geological mapping and interpretation. Both the authors have published widely quoted papers of lasting value. They served the Geological Society of India in the challenging task of being successive editors to the Journal of the Society and have established editorial capabilities. It goes to the credit of these two earth scientists that they, in the present two volumes, provide an exhaustive and commendable synthesis of Indian geology, covering the major recent advances. They have thereby generated, perhaps, the almost up-to-date and authentic publication on the subject now available.

The authors have taken to a central path in areas of modeling diversity. Most evolutionary models find a mention in the text. Areas of geophysics and geochemistry are emphasized, but the main focus is on structure, tectonics, stratigraphy and the geological milieu. Though the Global Stratigraphic Scale is broadly followed, formations are described keeping in view their spatial and temporal continuity. Such a presentation has the merit of ensuring a wholesome picture of the geological history behind each of these geological entities which will be lost when mutilated into the various systems in the International Time Scale. Thus the Precambrian is described in terms of cratons, mobile belts and Proterozoic platformal sediments. Precambrian stratigraphy is well integrated with petrology and chemistry. In the Phanerozoic, considerable emphasis is laid on sequence stratigraphy in different regions and life (mega and micro) preserved in fossils during different periods. The Gondwana and the Siwalik sequences are described as single entities. The write-up on the Deccan and Rajmahal volcanism emphasises the several manifestations of the riftogenic episodes of continental volcanism, their chemical stratigraphy, petrology and petrogenesis. The Precambrian of the Himalaya is described in a chapter along with other Mobile Belts in Volume 1 and the Phanerozoic of the Himalaya in the successive chapters on Palaeozoic, Mesozoic and the Cenozoic in Volume 2. Offshore basins constitute the penultimate chapter. Geomorphic evolution is appropriately reserved to the end of the book as the last chapter. The book presents a selected bibliography that lists most of the significant contributions. The authors are constrained to be brief in several sections due to limitations of space.

I have been fortunate to be associated with the reviewing of several chapters at one stage or other and the final manuscript volume recently. I deem it a privilege to be requested by the Geological Society of India to write this Foreword to this book. A comprehensive treatise, the book would prove to be an up-to-date source of information on Indian continental geology. I recommend it for wide readership.

T. M. MAHADEVAN

# Preface to Reprint Edition

There was an overwhelming response from the earth scientists to this book and all copies are sold out already. In view of this great demand, the Geological Society of India has decided to reprint the book with minimal additions/alterations so that there is no change in pagination. We have fulfilled this mandate by taking into account the suggestions from experts like O.N. Bhargava, L.S. Chamyal, G. Lakshminarayana, U.B. Mathur, A.C. Nanda, G.V.R.K. Prasad, K.N. Prudhvi Raju, D.S.N. Raju and Vishwas S. Kale. Major changes added here synoptically pertain to the Pandyan and Eastern Ghats mobile belts in Chapter 4 and 'Purana' basins in Chapter 5. The new International Stratigraphic Chart or ISC (ICS, 2009) printed in this reprint replaces the ISC 2004 included in the 2008 Edition of the book. Elsewhere, a table each has been added as folder in Chapters 6 (Palaeozoic) and 8 (Mesozoic), contents in a few tables substantially modified in Chapters 10 (Cenozoic) and 12 (Offshore basins), and ages changed in a few places based on geochronological and faunal evidence.

New plate tectonics signatures such as ophiolites, eclogites and high P-T metamorphism in the Eastern Ghats and Pandyan mobile belts have been described recently and linked to global supercontinent dispersal and assembly. The time span of 'Purana' basins has been revised to Mesoproterozoic (1000 to 1600 Ma) on the basis of isotopic ages of the upper sequences at ~1000 Ma (e.g. Bhander, Bhima / Kurnool, Chhattisgarh etc.) negating the earlier views of their Neoproterozoic ( ~500 Ma) age.

A Supplementary Bibliography has been added at the end of each volume to reflect the rapid changes happening in the geology of India. We have by and large laid emphasis on stratigraphy while making these changes. The recent book "The Making of India – A Geodynamic Evolution" by K.S. Valdiya (2010), published by Macmillan (816p), is a valuable companion that deals with the geology of Himalaya and neighbouring regions (Pakistan, Tibet, Nepal, Bhutan, Myanmar, Sri Lanka and the Indian Ocean) in greater detail, covers broadly the Phanerozoic geology of India and contains an exhaustive list of references. Another recent book "Cratons and Fold Belts of India" by R.S.Sharma (2009) published by Springer (304p) is a useful supplement that compares and contrasts different evolutionary models, starting with an introduction to Precambrian terrains and tectonics.

We are grateful to the MSPL Limited, Hospet for liberal financial assistance for printing of this book.

The series of Memoirs released by the Geological Society of India in connection with the Golden Jubilee Celebrations in 2008 that highlight the advances made in different fields of the earth sciences in India are valuable sources of reference. These developments reflect the burgeoning progress of research and we could only provide a glimpse of it given the time and space constraints. We thank the Geological Society of India for its pro-active role.

*31st May 2010* R.VAIDYANADHAN
M.RAMAKRISHNAN

# Preface

Geology came to occupy the pride of place in the country following Independence and rapid industrialization based on Five Year Plans of the Nehru era. Geological Survey of India, the premier earth science organization in the country, was considerably expanded and decentralized to the various States of India. National Research Institutes like the NGRI, PRL, CESS, WIHG, BSIP etc. were encouraged to develop rapidly, and the Universities urged to become centers of excellence. The net result of the combined activity was the production of wealth of new data, forming the backbone for industrial advancement. The dissemination of new information was originally confined to specialist publications of limited circulation. The classical textbooks by D.N. Wadia and M.S. Krishnan, which met the requirements until the seventies, were fast becoming obsolete. The few books that appeared later had limited size and scope, and did not meet the popular demand. E.H. Pascoe's Manual in four volumes as well as the Revised Fourth Edition of the Manual of Geology of India by GSI are too big for general use. Specialized publications on the Precambrian of India and on the Indian plate as a whole mainly catered to specific sections of the geological community. The need for a textbook suitable for teaching, research and search for economic minerals was sorely felt soon. The present volume containing the collated and condensed data is designed to meet these needs. Its target readership is not only students, but also research scholars and professional scientists. The Geological Society of India, which pioneered the publication of textbooks on the States of India, has taken the lead to publish this volume also.

Classical geology is firmly rooted in stratigraphy, in conjunction with structural geology in deformed terrains. Stratigraphy is fundamental for building models of metamorphism, tectonics and crustal evolution, and is therefore the prime focus of this book. The scheme follows the recent (2004) International Stratigraphic Scale. The Code of Stratigraphic

Nomenclature is not rigorously adopted in India, and therefore some deviations are noticed in the correlation tables reproduced here from authors, who worked in different terrains in different periods. In some cases the names of the stages given earlier are different from those in vogue now. The most popular and widely quoted stratigraphic schemes are used in the book to maintain an even balance. The geology of India is a rich tapestry of geological history from the Archaean to the present day, of which the Himalaya as a classical example of continental collision, the Deccan Volcanic Province as an important Large Igneous Province of global importance, the 'Purana' Basins, a variety of greenstone belts and the typical granulite terrain forming the type area of charnockites have been the recent focus of international attention. In order to do reasonable justice to its complex geology and flood of new data, the book is organized into two volumes, broadly dealing with the Precambrian (Volume 1) and the Phanerozoic (Volume 2). R. Vaidyanadhan has written the Chapter 1 and the Phanerozoic part of Chapter 2 in Volume 1; and the Inter-trappean part of Chapter 9, and the Chapters 6, 7, 8, 10, 11, 12 and 13 in Volume 2. M. Ramakrishnan has written the Precambrian part of Chapter 2 and the Chapters 3, 4 and 5 in Volume 1; and the Deccan Trap part of Chapter 9 in Volume 2.

The Precambrian of India has been dealt with in terms of tectonic divisions like cratons, mobile belts and flat-lying cratonic basins. It is our belief that such genetic divisions are more durable than the ones based on geographical regions, chronostratigraphic schemes or those based on crustal evolution. The latter two criteria are subject to frequent change due to revolutionary changes in geochronology or the emergence of new paradigms like plate tectonics or its variant of plume tectonics. The core of the book has, however, the flexibility to accommodate any foreseeable new developments.

In the case of the Phanerozoic, the stratigraphy is presented in the conventional manner giving importance to sequence, lithology, life and broad correlation within each era. Gondwana and Siwalik are, however, dealt with separately since they occupy conspicuous special range in time and space in Indian stratigraphy with overlaps in time when compared with the standard International Stratigraphic Scale (Gondwana from part of Palaeozoic to Mesozoic era and Siwalik from Miocene to Pleistocene epochs within the Cenozoic era). A brief presentation is made from the voluminous data published by ONGC on Offshore basins over the past half-a-century. Morphology and evolution of sections of Indian subcontinent come at the end to complete the story of the geology of India.

The Selected Bibliography at the end is not exhaustive and is largely limited to reviews or overviews, and to some of the recent ones that make any specific new viewpoint or present new data. Any omission in this regard is not intentional. Similarly, the references are not cited in the text at frequent intervals in order that the flow of the narrative is least interrupted. A substantial part of the text is drawn from the textbooks and memoirs of the Geological Society of India, regular and Special Publications of the Geological Survey of India and Proceedings of Seminars, besides important articles from the national and international journals.

Geological Map of India on 1:5 M scale published by the Geological Survey of India (GSI) in 1993 is included in this book for reference. The 'Legend' in the map may not correspond with the scheme used in the book, but the geological units in the map will form a useful guide. For additional information, the geological, tectonic, geomorphological and other thematic maps on 1:2 M scale published by GSI may be consulted.

We are grateful to the Department of Science and Technology, Government of India, New Delhi for a generous grant for publication of the book.

Padmashree (Dr.) B.P. Radhakrishna is the main source of inspiration for this volume. Without his constant goading and monitoring, it would not have been possible to complete this book.

R. Vaidyanadhan
M. Ramakrishnan

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Padmashri B.P.Radhakrishna, the doyen of Indian geology, has been a great source of inspiration and constant guidance in our endeavour. We owe a deep debt of gratitude to Prof. T.M.Mahadevan, who perused the manuscript critically and patiently, and offered very valuable suggestions for improvement. His sound geophysical understanding of geological problems was a great asset to us in his incisive review. He is also thanked for the Foreword to this book. He and Dr.S.M.Naqvi of the National Geophysical Research Institute, Hyderabad, have made the final appraisal of the manuscript volume, on behalf of the Department of Science and Technology, Government of India. Almost all the chapters of the book have been reviewed by at least two experts in the respective fields and we are grateful to them for sparing their valuable time. The experts in the alphabetical order are: O.N. Bhargava, L.S.Chamyal, A.Govindan, Jai Krishna, A.K. Jain, Vishwas S. Kale, Vivek S. Kale, GLakshminarayana, A.C. Nanda, K.N.Prasad, D.S.N.Raju, K.N.Prudhvi Raju, GN.Rao, P.K.Saraswati, S.V.Srikantia, K.V.Subbarao, S.K.Tandon, R.C.Tewari, S.Viswanathan (Hyderabad), S.Viswanathan (Mumbai) and P.L. Zutschi. K.V. Subbarao is particularly thanked for help with the illustrations and literature on Deccan Traps. It must be admitted, however, that due to constraints of space, some of the well-meaning suggestions of the experts could not be incorporated in the book.

A host of friends and well-wishers have been of valuable help in providing us with notes, reprints, manuscripts, drawings, photographs, imagery, fossil plates and photocopies. Among them mention may be made of the following persons in the alphabetical order: Abhinaba Roy K.Ayyasamy, S.Balakrishnan, P.K.Banerji, N.P. Bhatt, A. Bhattacharyya, T.K. Biswal, GCh. Chennaiah, R.K. Ganjoo, N.C. Ghose, H.K. Gupta, M. Hanuma Prasad, A.K. Jaitley, M. Jayananda, V.K. Jha, G Lakshminarayana, C.Leelanandam, Y.V.N. Krishnamurthy, S. Madabhushi, Mahadev, U.B. Mallikarjuna, R.K.Mazari, N.C. Mehrotra, K.S. Misra,

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We are thankful to Mahaveer and Siddu Kalagudi of MSPL Ltd. (Baldota), Bangalore, R.H. Rajiv of Geomysore Services, Bangalore, and Naga Murari and Madan Mohan of Mumbai for digitization of some figures. We are thankful to R.H. Sawkar, V.N. Vasudev and K.V. Subbarao for coordinating the digitization of some figures. Nagaraju of Driti Enterprises, Bangalore is thanked for undertaking the task of printing and binding with customary zeal.

We are grateful to a host of publishing houses listed under "Permissions" in each volume and copyright holders who have generously granted us permissions to reproduce illustrations from various publications. The main sources are the Geological Society of India, Geological Survey of India, Elsevier Scientific Publishers, Current Science, Prof. A.B.Roy and Scientific Publishers (India), Jodhpur, and Gondwana Geological Society, Nagpur. Many other sources, which have enriched the book, are listed under Permissions.

We are grateful to the Geological Society of India, Bangalore for acceding to our request for publication of the book. B.P. Radhakrishna, H.K. Gupta, M.S. Rao and R.H. Sawkar have evinced keen interest in speedy publication. The following staff of the Geological Society of India are thanked for their prompt help in many ways in the preparation of the book: Subhash Chandra, Jitendra Kumar, S. Shivanna, Nagabhushana, Venkataramaiah, Dharam Raju, Meera, Nalini, Veena, Govindaraju and Seetharamiah.

The authors would like to express their gratitude to their spouses Lakshmi Vaidyanadhan and Saroja Ramakrishnan and their sons Sridhar and Ravi Vaidyanadhan and Anand and Kartik Ramakrishnan and their families, who have been a great source of strength during the trying times on this seemingly endless journey towards our goal, spanning many years. M.Ramakrishnan offers his obeisance to Agastya Mahamuni, Lopamudra Devi and Pradhanacharya of Gnana Kendra (A.N.Shankar) in Bangalore for their blessings in this project.

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R. VAIDYANADHAN
M. RAMAKRISHNAN

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| Wadia Institute of Himalayan Geology | 1.4, 1.6, 1.8 |
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| Indian Journal of Geomorphology, Thanjavur | 1.8 |
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# 1

# Introduction and Physiography

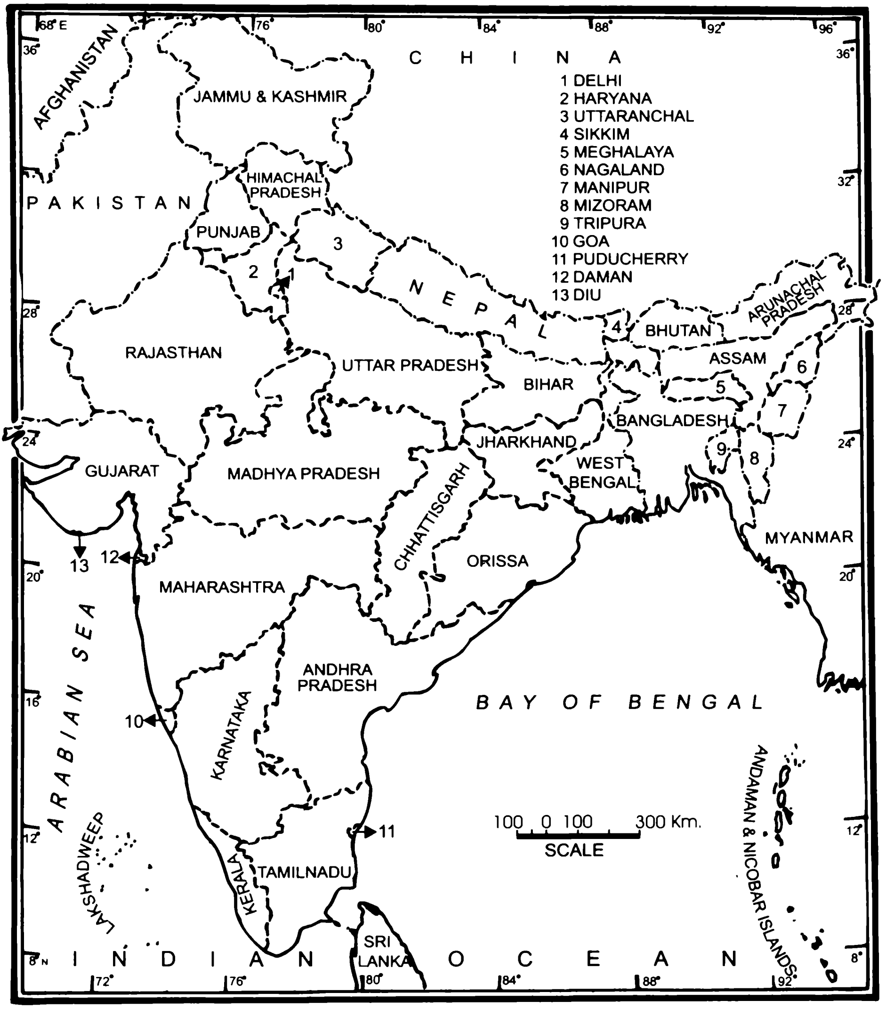
## INTRODUCTION

The Indian subcontinent is a conspicuous physical entity in a map of the Asian continent. In the north it is bordered by the Himalaya Mountains and it is surrounded by Arabian Sea in the west, Indian Ocean in the south and Bay of Bengal in the east. Within the subcontinent three major divisions will become evident. These are usually referred to as Peninsular India in the south, the Extra-Peninsular India in the north and the Indo-Gangetic Plain in between. Each one of these has distinguishable geological and geomorphological characteristics.

For administrative purposes India is divided into 30 States and 5 Centrally Administrated Union Territories (Fig.1.1). Of these, the States of Uttarakhand, Jharkhand and Chhattisgarh have been only recently (2000-2002) carved out of Uttar Pradesh, Bihar and Madhya Pradesh States respectively. Pondicherry State is now named as Puducherry.

Peninsular India is made of many mountain chains, plateaus and narrow coastal plains, interspersed with deltas and estuaries. Deformed igneous, sedimentary and metamorphic rocks are met with and they host enclaves of some of the oldest rocks of the Earth (>3300 Ma). The rocks and sediments range in age from Precambrian to the Holocene. The landscape consists of extensive high-level surfaces, some of which are dissected. Majority of the rivers flow from the west to the east into the Bay of Bengal, except for the rivers Narmada and Tapti, flowing due west.

The Extra-Peninsular India is made of very high rugged mountain ranges of the Himalaya, separated by deep valleys. Majority of the rocks are sedimentary, though igneous and metamorphic rocks are also present. Most of them are Phanerozoic (<600 Ma) though Precambrian igneous and metamorphic rocks are also known. Folds and faults are clearly seen and thrust sheets can be visualised. Perennial rivers like Indus, Ganga (Ganges), Yamuna and Brahmaputra and some of their tributaries originate from different parts of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CHINA
1 DELHI
2 HARYANA
3 UTTARANCHAL
4 SIKKIM
5 MEGHALAYA
6 NAGALAND
7 MANIPUR
8 MIZORAM
9 TRIPURA
10 GOA
11 PUDUCHERRY
12 DAMAN
13 DIU
AFGHANISTAN
JAMMU & KASHMIR
HIMACHAL PRADESH
PAKISTAN
PUNJAB
NEPAL
ARUNACHAL PRADESH
BHUTAN
RAJASTHAN
UTTAR PRADESH
BIHAR
ASSAM
BANGLADESH
JHARKHAND
WEST BENGAL
GUJARAT
MADHYA PRADESH
CHHATTISGARH
ORISSA
MYANMAR
MAHARASHTRA
ARABIAN SEA
ANDHRA PRADESH
KARNATAKA
BAY OF BENGAL
ANDAMAN & NICOBAR ISLANDS
100 0 100 300 Km.
SCALE
LAKSHADWEEP
KERALA
TAMILNADU
SRI LANKA
INDIAN OCEAN

**Fig.1.1.** States of the Indian Union.

Himalaya and the neighbourhood. Some of the major rivers pass through deep gorges cutting across the ranges, before flowing down south on to the plains.

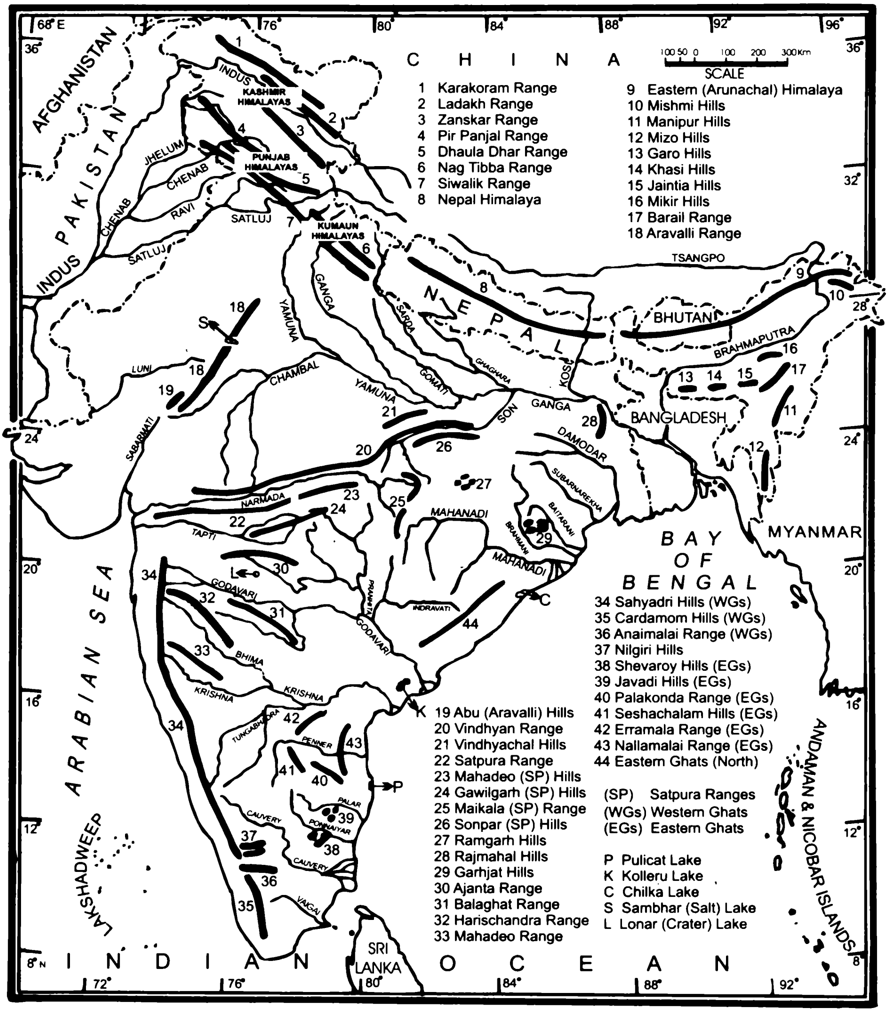
The Indo-Gangetic Plain, into which the rivers mentioned above enter, is an extensive plain, sloping gently due east-southeast. The unconsolidated sediments in this plain are derived both from the Himalaya in the north and the shield in the south, though more from the north. This is one of the greatest foredeeps in the world. Alluvial fans along the northern borders, terraces and flood plains are common features. The rivers, which meander and are braided in many places, present a variety of landforms. Though the Ganga basin might have been initiated during the Tertiary (<65 Ma), the sediments in them are essentially Quaternary in age (<2 Ma). This is mainly because the uplifted mountains became a provenance for these sediments in late Tertiary only (<20 Ma).

A brief description of some of the physical features and characteristics of the mountains, glaciers, rivers, lakes, coasts and the seas around is given here followed by an introduction to climate, soil, natural vegetation and groundwater. In India there are landforms formed practically due to all geological agents of erosion and deposition though those due to Pleistocene continental glaciation are absent or not widely recognised.

## PHYSICAL FEATURES

### Mountains

Prominent mountain ranges of Peninsular and Extra-Peninsular India are shown in Fig.1.2. The Himalayan Mountains in the north have the loftiest of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C H I N A
100 50 0 100 200 300Km
SCALE
1 Karakoram Range
2 Ladakh Range
3 Zanskar Range
4 Pir Panjal Range
5 Dhaula Dhar Range
6 Nag Tibba Range
7 Siwalik Range
8 Nepal Himalaya
9 Eastern (Arunachal) Himalaya
10 Mishmi Hills
11 Manipur Hills
12 Mizo Hills
13 Garo Hills
14 Khasi Hills
15 Jaintia Hills
16 Mikir Hills
17 Barail Range
18 Aravalli Range
AFGHANISTAN
PAKISTAN
INDUS
KASHMIR HIMALAYAS
PUNJAB HIMALAYAS
KUMAUN HIMALAYAS
JHELUM
CHENAB
RAVI
SATLUJ
LUNI
SABARMATI
GANGA
YAMUNA
SARDA
GHAGHARA
GOMATI
KOSI
SON
CHAMBAL
TSANGPO
NEPAL
BHUTAN
BRAHMAPUTRA
BANGLADESH
DAMODAR
SUBARNAREKHA
BAITARANI
BRAHMANI
MAHANADI
NARMADA
TAPTI
GODAVARI
INDRAVATI
PRANHITA
BHIMA
KRISHNA
TUNGABHADRA
PENNER
PALAR
PONNAIYAR
CAUVERY
VAGAI
MYANMAR
BAY OF BENGAL
ARABIAN SEA
LAKSHADWEEP
SRI LANKA
INDIAN OCEAN
ANDAMAN & NICOBAR ISLANDS
S
L
C
K
P
34 Sahyadri Hills (WGs)
35 Cardamom Hills (WGs)
36 Anaimalai Range (WGs)
37 Nilgiri Hills
38 Shevaroy Hills (EGs)
39 Javadi Hills (EGs)
40 Palakonda Range (EGs)
41 Seshachalam Hills (EGs)
42 Erramala Range (EGs)
43 Nallamalai Range (EGs)
44 Eastern Ghats (North)
19 Abu (Aravalli) Hills
20 Vindhyan Range
21 Vindhyachal Hills
22 Satpura Range
23 Mahadeo (SP) Hills
24 Gawilgarh (SP) Hills
25 Maikala (SP) Range
26 Sonpar (SP) Hills
27 Ramgarh Hills
28 Rajmahal Hills
29 Garhjat Hills
30 Ajanta Range
31 Balaghat Range
32 Harischandra Range
33 Mahadeo Range
(SP) Satpura Ranges
(WGs) Western Ghats
(EGs) Eastern Ghats
P Pulicat Lake
K Kolleru Lake
C Chilka Lake
S Sambhar (Salt) Lake
L Lonar (Crater) Lake

Fig.1.2. Mountains, rivers and lakes.

peaks of which the Mount Everest is the highest (~8848 m). These extend in an arcuate form over a length of about 2500 km from Pamir (beyond Karakoram Range) in the west to Mishimi Hills in the east, with the convexity to the south. The width varies between 150 and 400 km. There are ~14 peaks more than 8000 m high and many more over 7000 and 6000 m. It may be interesting to note that there are a few mounts in the ocean floors, which rise to heights comparable to those of the peaks in the Himalaya and some even taller from their base. Though the main range is in India, Nepal and Bhutan, the northern slopes extend into the Tibetan Plateau. The main range can be divided into Tethys domain, Himadri (Great Himalaya), Lesser Himalaya and Siwalik (Outer Himalaya) (Fig.1.3), between Tibet in the north and the Indo-Gangetic Plain in the south. There are two major syntaxial bends one in the northwest called Nanga Parbat, a little beyond Karakoram range, and the other called Namcha Barwa in Arunachal Pradesh in the extreme northeastern part of the country. Most of the peaks are snow covered and there are many glaciers in them particularly in the Tethys domain and Great Himalaya. Geographically, as one traverses from northwest parts of the Himalaya towards east, they are called Kashmir Himalaya, Himachal Himalaya, Kumaun-Garhwal Himalaya, Nepal Himalaya, Bhutan Himalaya, Assam Himalaya and Arunachal Himalaya. These high mountains have been formed by the collision of Indian plate with the northern Asian plate. A series of overthrusts from the east has resulted in the mountains/hill ranges in the northeastern region, Myanmar, Andaman and Indonesia.

In Peninsular India the major landforms are the Western Ghats (*Sahyadri*), close to the west coast, and the Eastern Ghats, partly close to the east coast. Right across Peninsular India are the Vindhyan and Satpura Ranges.

The Western Ghats is a continuous escarpment extending from southern Gujarat to Kerala (~1600 km) except for a break in the far south called Palghat Gap between Nilgiri Hills and Anaimalai Ranges. The Gap has a maximum width of about 24 km and an elevation of about 70 m amsl and is a conspicuous low level landform along 10°45'N Lat. The highest peak in the Western Ghats is Anaimudi (2693 m), to the south of Palghat Gap, followed by Doddabetta (2636 m) in the Nilgiris, to the north of the Gap. The Western Ghat forms a watershed for all the rivers flowing east and west. Their easterly slopes are gentle. But the western ones are steep, presenting long escarpments, particularly in Maharashtra and northern Karnataka. In Maharashtra the highest peaks are Kalsubai (1646 m) and Salhar (1567 m). Almost the northern half of the Western Ghats is made up of the Deccan Trap (Cretaceous-Paleocene lava flows), the central part by Dharwar schist belts and the southern part by Precambrian charnockites, granites and gneisses. The Deccan Plateau to the east of the Western Ghats is essentially made of Deccan Trap in the north and Precambrian rocks in the south, the southern part designated as the Mysore Plateau. Though the present day topography is largely due to erosion, its origin is due to dismemberment of sections of Eastern Gondwanaland followed by easterly tilt due to rifting along the west coast, along the major NNW-SSE lineament. In this case a major fault separated southern Africa from Peninsular India and the topography on either side reflects this separation, namely easterly slope in India and westerly slope in Malagasy (Madagascar).

The Eastern Ghats comprise of a series of detached hills extending from Shevaroy and Javadi Hills in Tamil Nadu in the south to Orissa in the northeast, a major continuous stretch being in north coastal Andhra Pradesh. The maximum elevation attained is ~1500 m at Mahendragiri in Orissa. Most of the Eastern Ghats is formed by charnockites, khondalites and migmatitic gneisses of Eastern Ghats mobile belt, Nallamalai fold belt of Proterozoic Cuddapah basin, made up of quartzites, slates, shales and limestones, and charnockites and high grade gneisses of Tamil Nadu in the Shevaroy and Javadi Hills. Parts of the Ghats have flat tops with laterite (bauxite) cappings.

The Vindhyan and Satpura Ranges, extending ENE-WSW are partly made up of hill ranges and partly plateaus. The Vindhyan Range extends from Jobat in Gujarat in the west and ends up in Bihar near Sasaram in the east. The general elevation ranges between 450 and 600 m, but a few ranges rise to 900 m. They are mostly composed of sandstones and quartzites of the Vindhyan Supergroup. The Satpura Range, though shorter, attains greater elevations (Pachmarhi – 1335 m; Amarkantak – 1064 m). These are made up of Deccan Traps, Gondwana sedimentaries, Proterozoic sedimentary rocks and Precambrian metamorphics, granites and gneisses. Their disposition is largely due to the major ENE-WSW thrusting along Narmada and Tapti faults and intermittent rejuvenation and erosion. The Chhotanagpur Plateau (major part of Jharkhand State) is made of Precambrian formations bound by the Gangetic Plain to the north. Rajmahal Hills comprise the eastern edge of the Late Mesozoic Rajmahal flows and inter-trappean beds and trend nearly N-S.

The Aravalli Hills in Rajasthan extend SW to NE from Gujarat to south of Delhi. The highest point is Gurusikhar (1722 m) in Mt. Abu. Geophysical studies have established their extension further northeast beneath the Gangetic alluvium. These are made up of Precambrian igneous, metamorphic and sedimentary rocks. Their position is mainly due to a major thrust from the east and periodic uplift and faulting.

The Shillong Plateau in the northeast is made up of Garo, Khasi and Jaintia Hills. They are considered as possible extension of the ENE-WSW trending

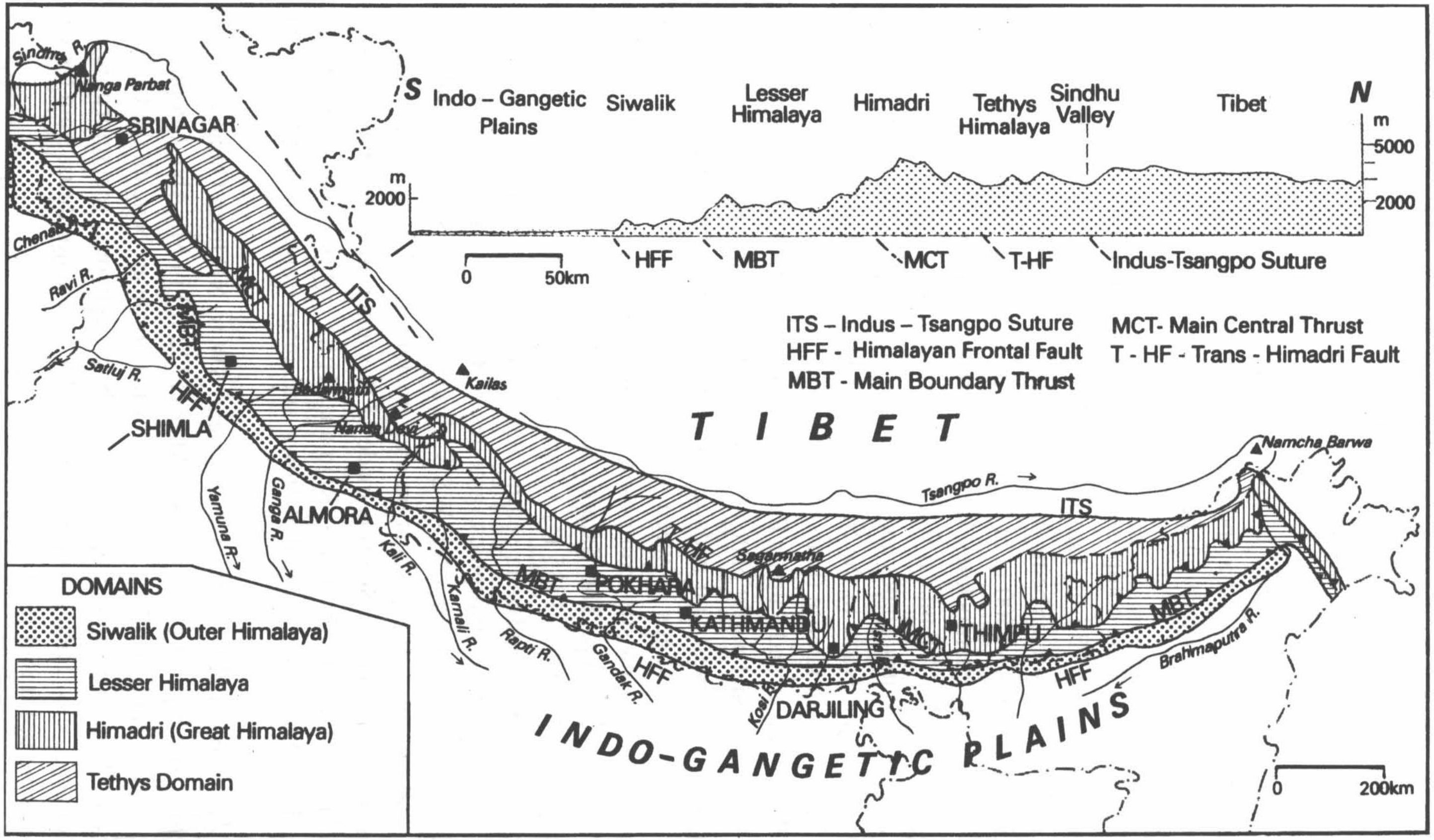

S
Indo – Gangetic Plains
Siwalik
Lesser Himalaya
Himadri
Tethys Himalaya
Sindhu Valley
Tibet
N
m
5000
2000
m
2000
0
50km
HFF
MBT
MCT
T-HF
Indus-Tsangpo Suture
ITS – Indus – Tsangpo Suture
HFF - Himalayan Frontal Fault
MBT - Main Boundary Thrust
MCT- Main Central Thrust
T - HF - Trans - Himadri Fault
Sindhu R.
Nanga Parbat
SRINAGAR
Chenab R.
Ravi R.
Satluj R.
SHIMLA
MBT
MCT
ITS
HFF
Kailas
Badarinath
Nanda Devi
Yamuna R.
Ganga R.
ALMORA
Kali R.
Karnali R.
Rapti R.
Gandak R.
Kosi R.
T I B E T
Namcha Barwa
Tsangpo R.
ITS
T-HF
Sagarmatha
MBT
POKHARA
KATHMANDU
THIMPU
MCT
HFF
HFF
MBT
Brahmaputra R.
DARJILING
INDO-GANGETIC PLAINS
0
200km
DOMAINS
Siwalik (Outer Himalaya)
Lesser Himalaya
Himadri (Great Himalaya)
Tethys Domain

**Fig.1.3.** Physiographically distinctive and geologically contrasted terranes or subprovinces of the Himalaya. In the upper part a simplified profile of the Himalaya along the line marked by two arrows (after Valdiya, 1998, p.10; Published by arrangement with Universities Press (India) Pvt. Limited).

Vindhyan and Satpura Ranges, though separated by the Rajmahal Gap in West Bengal and Bangladesh. As the very name signifies it is essentially a plateau made up of Precambrian igneous and metamorphic rocks in a major part. It owes its position essentially to uplift, squeezed up between northward drifting Indian plate and the Asian plate in the north.

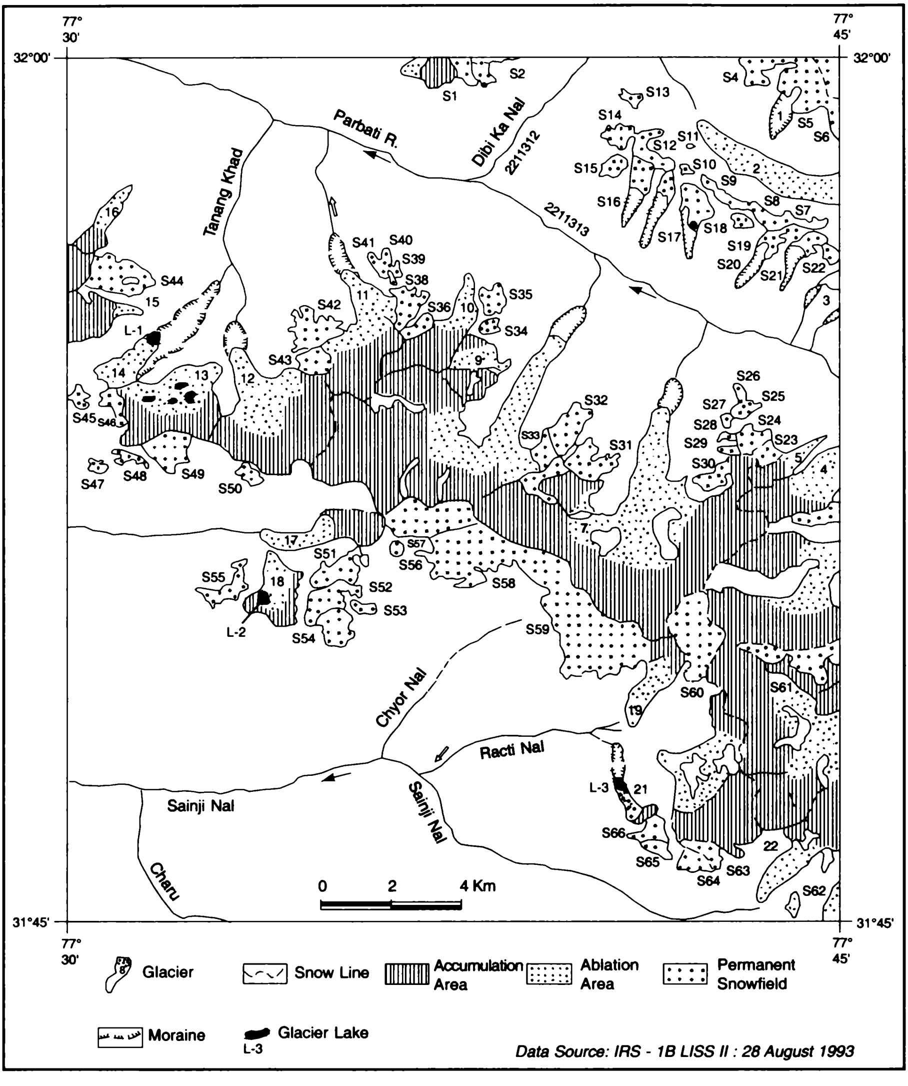
## Glaciers

Glaciers are frozen rivers of ice that flow from high mountain ranges, or are permanent features on continents like Antarctica, and Greenland. By melting, evaporation, wind erosion and breaking up of ice, glaciers sink and the annual loss of ice is called ablation. There are nearly 15,000 glaciers in the Himalaya, lying between the two syntaxial bends already referred to. They can range in size from 75 km to only 3 to 5 km in length. Almost 33,000 km$^2$ or 17% of the Himalaya is ice-clad, of which the Karakoram Range alone is covered by 16,000 km$^2$ of ice.

Glaciers originate in high mountains where the snow budget is positive i.e. where the winter accumulation exceeds summer ablation. The snout (end) of the glacier invariably descends well below the snowline, the lowest limit of perpetual snow. In general, snowline in the western Himalaya lies at about 5000 m, whereas in the Eastern Himalaya it is about 1000 m further above. On the northern side of the mountain ranges the snowline rises about 500 m in general. The accumulation and stability of snow depends upon the nature of precipitation, aspects, gradients of the topography, etc. The present glaciers are only remnants of the extensive glaciation of the Pleistocene epoch (~1.8 Ma to 10,000 yrs. B.P.) which covered very large mountainous tract in the Himalaya.

With the advent of remote sensing techniques it is possible to map the areal extent of glaciers in inaccessible areas as well. False Colour Composites prepared from visible and near-infra red satellite images are being used to map various glacial features such as glacial boundary, accumulation area, ablation area, equilibrium line and moraine-dammed lakes. Figure 1.4 presents an example of glacier inventory map prepared using satellite imagery and Table 1.1 presents length of some important glaciers. Since the melting of glaciers contributes substantially to the flow in the major Himalayan rivers from the north (apart from precipitation), monitoring their parameters is of considerable importance to estimate the quantum of flow into the major tributaries of these rivers during each year.

The Gangotri glacier in Central Himalaya, traditionally the source of Ganga, has numerous tributary glaciers. Its total surface area is about 200 km$^2$ and the total volume is estimated to be approximately 20 km$^3$ of ice. Because of the immense size of the Gangotri glacier, its meltwater stream – the river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32°00'
31°45'
Parbati R.
Dibi Ka Nal
Tanang Khad
Chyor Nal
Racti Nal
Sainji Nal
Charu
0 2 4 Km
Glacier
Snow Line
Accumulation Area
Ablation Area
Permanent Snowfield
Moraine
Glacier Lake L-3
Data Source: IRS - 1B LISS II : 28 August 1993

**Fig.1.4.** An example of glacier inventory map prepared using IRS-1B LISS 11 image (Date: 28 August, 1993) (source: Kulkarni et al.1999).

Bhaghirathi, (called Ganga in the downstream) is a full-fledged river even as it emerges (Fig.1.5) from the subglacial tunnel at the glacier terminus – the Gaumukh (cow's mouth) of Hindu mythology.

Himalayan glaciers have been retreating almost continuously, even though occasionally during certain short periods a few of them might have advanced a little. Table 1.2 gives the average rate of retreat of some of the Himalayan glaciers in the Himalaya and Karakoram.

Just as rivers are agents of erosion and deposition, glaciers too create a variety of landscapes and landforms through erosion and deposition. Among

**Table 1.1.** Length of important glaciers in Himalaya and Karakoram (source: modified after Mathur, 1991; Krishnan, 1982, p.12)

| Name | Location | Length (km) |
|---|---|---|
| Siachen | Karakoram | 75 |
| Hispar | Karakoram | 62 |
| Biafo | Karakoram | 59 |
| Baltoro | Karakoram | 58 |
| Batura | Karakoram | 58 |
| Rimo | Karakoram | 40 |
| Gangotri | Kumaun-Garhwal | 30 |
| Milam | Kumaun-Garhwal | 20 |
| Mana | Kumaun-Garhwal | 18 |
| Satopanth | Kumaun-Garhwal | 16 |
| Bhagirath-Kara | Kumaun-Garhwal | 18 |
| Chhota-Shigri | Pir Panjal | 9 |
| Sonapani | Pir-Panjal | 15 |
| Gangri | Pir-Panjal | 13 |
| Zemu | Nepal | 26 |
| Kanchenjunga | Nepal | 21 |
| Khumbu | Nepal | 20 |

the former are horn, cirque, arête, hanging valley and among the latter are different forms of moraines. Figure 1.6 is a geomorphological map showing the features usually associated with a glaciated mountainous area along with those of river issuing out of it in Kumaun-Garhwal Himalaya in Uttarakhand.

In the earlier years the areal extent of some of the accessible glaciers used to be mapped and rate of retreat or advance of the snout of the glaciers investigated, monitoring the same at regular periods over some years. The study of meltwater discharge, substantially contributing to the flow in the Himalayan rivers, has received some attention. Of late, apart from studies dealing with mass balance, glacier hydrometry, snout monitoring and suspended sediment transport, bedrock profiling is also made by geophysical methods, besides drilling, to estimate thickness of glacier ice. Lichenometry and tree ring study are resorted to for short-term dating of the glaciers and radiometric isotope studies coupled with those of spores and pollen, help in deciphering past climatic conditions in glaciated areas.

## Rivers

Majority of the rivers draining the Indo-Gangetic Plain have a large portion of their watersheds within the boundaries of the country in high mountainous regions in the form of permanent glaciers. Most of the winter

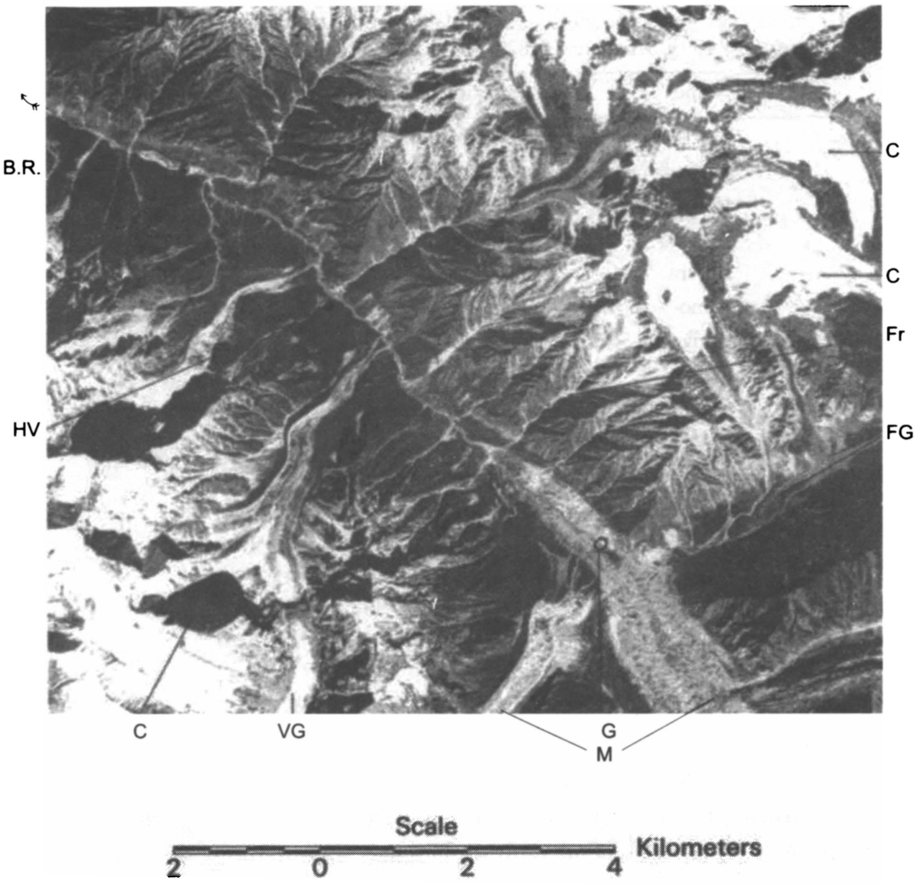
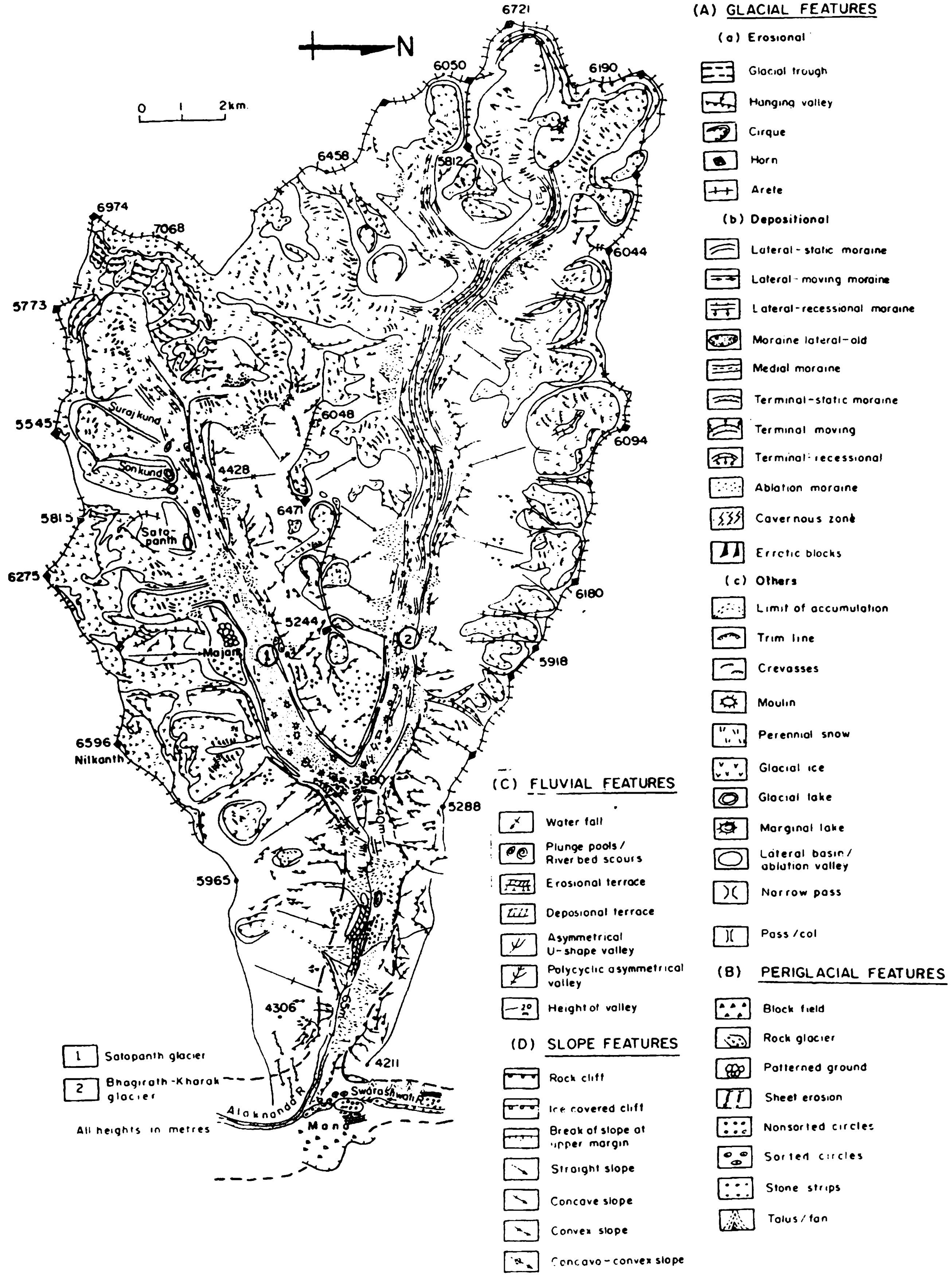


**Fig.1.5.** Morphology of Gaumukh and its environs, Uttaranchal Himalaya. M - Moraines, VG - Valley glacier, FG - Fluvioglacial deposits, C - Cirques, HV - Hanging valley, BR - Bhagirathi river, G - Gaumukh - origin of Bhagirathi River, Fr - Fractures (A. Bhattacharya, *pers. commn.*)

precipitation is retained in these glaciers as snow and is released in summer. The sources of Indus, Satluj and Karnali (the longest tributary of the Ganga), are all fairly close by within a few kilometres of each other in the neighbourhood of Manasarovar Lake in Tibet. Some of the Himalayan rivers passing through gorges across the strike ridges of Himalayan strata, with vertical sides rising more than 300 m above the river bed, are considered to be antecedent. They maintained their courses by deepening the valleys as the mountains were slowly undergoing uplift. Satluj flowing due west, joining Indus, Ganga flowing due south and Brahmaputra from the east are the major rivers issuing from the northern part of Himalaya. After passing through Tibet for about a distance of 1100 km as Tsang Po, Brahmaputra makes a loop around Namche Barwa peak, cuts through Himalayan ranges and passes through Assam valley in an extensive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5545
6048
6094
Sonkund
4428
5815
Satopanth
6471
6275
6180
5244
1
2
Majan
5918
6596
Nilkanth
3680
5288
40m
5965
4306
4211
Alaknanda R.
Swarashwati R.
Mana
1 Satopanth glacier
2 Bhagirath-Kharak glacier
All heights in metres
(A) GLACIAL FEATURES
(a) Erosional
Glacial trough
Hanging valley
Cirque
Horn
Arete
(b) Depositional
Lateral-static moraine
Lateral-moving moraine
Lateral-recessional moraine
Moraine lateral-old
Medial moraine
Terminal-static moraine
Terminal moving
Terminal-recessional
Ablation moraine
Cavernous zone
Erratic blocks
(c) Others
Limit of accumulation
Trim line
Crevasses
Moulin
Perennial snow
Glacial ice
Glacial lake
Marginal lake
Lateral basin/ablation valley
Narrow pass
Pass/col
(B) PERIGLACIAL FEATURES
Block field
Rock glacier
Patterned ground
Sheet erosion
Nonsorted circles
Sorted circles
Stone strips
Talus/fan
(C) FLUVIAL FEATURES
Water fall
Plunge pools/River bed scours
Erosional terrace
Depositional terrace
Asymmetrical U-shape valley
Polycyclic asymmetrical valley
Height of valley
20
(D) SLOPE FEATURES
Rock cliff
Ice covered cliff
Break of slope at upper margin
Straight slope
Concave slope
Convex slope
Concavo-convex slope

**Fig.1-6.** Geomorphological map of Satopanth-Bhagirath-Kharak glacier, Kumaon-Garhwal Himalaya, Uttaranchal (after Sah, 1991)

**Table 1.2.** Retreat of glaciers in the Himalaya and Karakoram (source: Vohra, 1981, p.141)

| Glacier | Time span | Total no. of years | Retreat in metres | |
|---|---|---|---|---|
| Milam | 1849-1957 | 108 | 1350 | HIMALAYA |
| Pindari | 1845-1966 | 121 | 2840 | |
| Shankulpa | 1881-1957 | 76 | 518 | |
| Poting | 1906-1957 | 51 | 262 | |
| Glacier No.3 in Arwa Valley | 1932-1956 | 24 | 198 | |
| Gangotri | 1935-1976 | 41 | 600 | |
| Zemu | 1909-1965 | 56 | 440 | |
| Bara Shigri | 1940-1963 | 23 | 1019 | |
| Sonapani | 1906-1963 | 57 | 905 | KARAKORAM |
| Minapin | 1906-1929 | 23 | 502 | |
| Biafo | 1861-1922 | 61 | 0 | |
| Kichik Kumdam | 1946-1958 | 12 | 1219 | |
| Siachen | 1929-1958 | 29 | 914 | |
| Yengutsa | 1892-1925 | 33 | 4134 | |

wide braided channel. Passing around Garo Hills, it joins Ganga in Bangladesh where it is called Padma or Jamuna.

Among the Peninsular rivers, Godavari, Krishna and Cauvery (Kaveri) have their sources in the Western Ghats and flow right across the country along with their numerous tributaries to discharge into the Bay of Bengal with prominent deltas at their mouths. Further north, the Mahanadi with its source in the northern foothills of Dandakaranya flows through a wide basin and joins the Bay of Bengal, building a very large delta, along with Baitarani and Brahmani to its north. Narmada and Tapti (Tapi) rivers flowing due west are the only two major rivers that discharge into the Arabian Sea, though there are many small rivers issuing from the western slopes of Western Ghats and discharging into the Arabian Sea. A rift or fault is considered to tectonically control the Narmada river. The Narmada-Son lineament is a major line of crustal dislocation. However, in spite of its location in a tectonically active zone in a monsoon setting, it is the exceptional high magnitude floods at irregular intervals that are considered responsible for the form and behaviour of the Narmada river. Tapti river originating in the Betul Plateau in Central India flows through a narrow gorge in the source region. Both Narmada and Tapti discharge through estuaries and have not built deltas.

Of late considerable interest has been aroused, thanks to recognition by remote sensing techniques, of rivers that flowed earlier in parts of Western Rajasthan, but no longer present now. One of them was the river Saraswati, whose now concealed course was suspected based on records in mythology and ancient history and some inferences based on ground survey. Its former existence is now confirmed beyond doubt. Luni river is possibly a remnant of one of the branches of the earlier Saraswati river. Numerous ancient settlements have been unearthed, which are considered to have thrived along the earlier banks of the lost Saraswati river. However, the manner in which the earlier channels migrated, shifted or disappeared and their chronological sequence are the points on which there is as yet no unanimity.

*Sediment yield:* One of the problems connected with the study of rivers attracting the attention of the scientific community is the nature and quantum of the sediments they carry and deposit either in the reservoirs or lakes or into the sea/ocean, where they ultimately discharge. A study of sediment yield has long time applications. Indian rivers show pronounced seasonal and spatial variability in their sediment discharge. It is surmised that besides contribution from the nature of the lithology of the drainage basin, anthropogenic activities also add to the sediment load. Table 1.3 gives the sediment yield as estimated for some of the rivers in the Indian subcontinent.

The amount of sediment that has been carried by the Himalayan rivers, since perhaps Late Miocene (~10 Ma) can be gauged by the growth of the Bengal basin which has been serving as a depositional centre. The giant delta of the two major rivers passes into the world's largest submarine fan, the Bengal Fan, whose frontal lobes extend to the south as far as 7° S, about 3000 km south of the delta's coastline. The sediment thickness in the fan is estimated to be >20 km.

**Table 1.3.** Sediment yield of rivers in the Indian subcontinent (source: Subramanian, 1993, p.928, Table 1)

| River | Basin area ($km^2$) | Run-off ($10^6$ $m^3$/yr) | Sediment load ($10^6$ t/yr) |
|---|---|---|---|
| Ganga | 7,50,000 | 4,93,000 | 329 |
| Brahmaputra | 5,80,000 | 5,10,000 | 597 |
| Indus | 9,70,000 | 2,38,000 | 100 |
| Irrawady | 4,30,000 | 4,22,000 | 265 |
| Narmada | 87,9000 | 46,7000 | 70 |
| Tapti | 49,000 | 18,000 | 25 |
| Godavari | 3,13,000 | 92,200 | 170 |
| Krishna | 2,51,400 | 32,400 | 4 |
| Mahanadi | 41,000 | 54,500 | 15.7 |
| Mahi | 25,500 | 11,000 | 9.7 |
| Brahmani | 28,200 | 16,300 | 20.4 |
| Kaveri | 66,300 | 21,500 | 1.5 |

*Floods:* These have been an almost annual feature, causing considerable destruction of life and property in different parts of India, more in the north than in the south. It is not as though, as one normally presumes, that the peak flood in any river is after a high incidence of rainfall in the catchment area. In quite a number of cases, it has been found that other factors like time interval between two successive rain storms, monsoon breaks, drainage and basin morphology, vegetation cover, antecedent precipitation, anthropogenic effects etc. play a part. It is also found that the magnitude of floods is not necessarily high in the Himalayan rivers such as Ganga and Brahmaputra. Flood power values in bedrock gorges, as for instance in Narmada, were found to be several orders of magnitude higher.

## Lakes

Lakes, bodies of naturally accumulated water, usually confined on all sides, can occur on mountain tops as well as along coastal plains. They form in glaciated areas in cirques (tarn), as glacial-dammed lakes, and as kettles in moraines. Sometimes they can be found along the course of large rivers as well, as in the case of Wular Lake in Kashmir. This lake occurs at an elevation of about 1578 m in the course of the Jhelum river. The lake water is spread over an area of 32.5 km$^2$ and swells over to 56 km$^2$ during floods. There are other lakes like Dal in Kashmir and Nainital in Uttaranchal. Some lakes are formed in flood plains in detached oxbows, called oxbow lakes or *bhils* or mortlakes. Many of these are met with in the flood plains of Ganga in Bihar and U.P. and Brahmaputra in Assam valley. They are also found in depressions caused by deflation in arid areas by the action of wind, filled with meteoric water, even if the precipitation is scanty, as in parts of Rajasthan. They also form along the coast, usually parallel to the coastline, separated from the sea by a spit or bar, but often with a narrow outlet to the sea, called a lagoon as in the case of Chilka and Pulicat lakes along the east coast. Some lakes are formed due to subsidence caused by dissolution of limestones.

In India there are examples of all these types. There are numerous ice-dammed lakes in the Himalaya. Some in the valleys are also due to massive landslides falling across flowing rivers. A danger in either case is the possibility of breach in them resulting in sudden release of great volumes of water causing destruction at lower elevations, usually downstream.

Saline lakes in Rajasthan are not only formed in deflation hollows, but also in depressions caused by tectonic disturbance, resulting from irregular movements along half-grabens. Sometimes they are found behind obstacles on the lee side, enclosed by longitudinal dunes. They usually have centripetal or

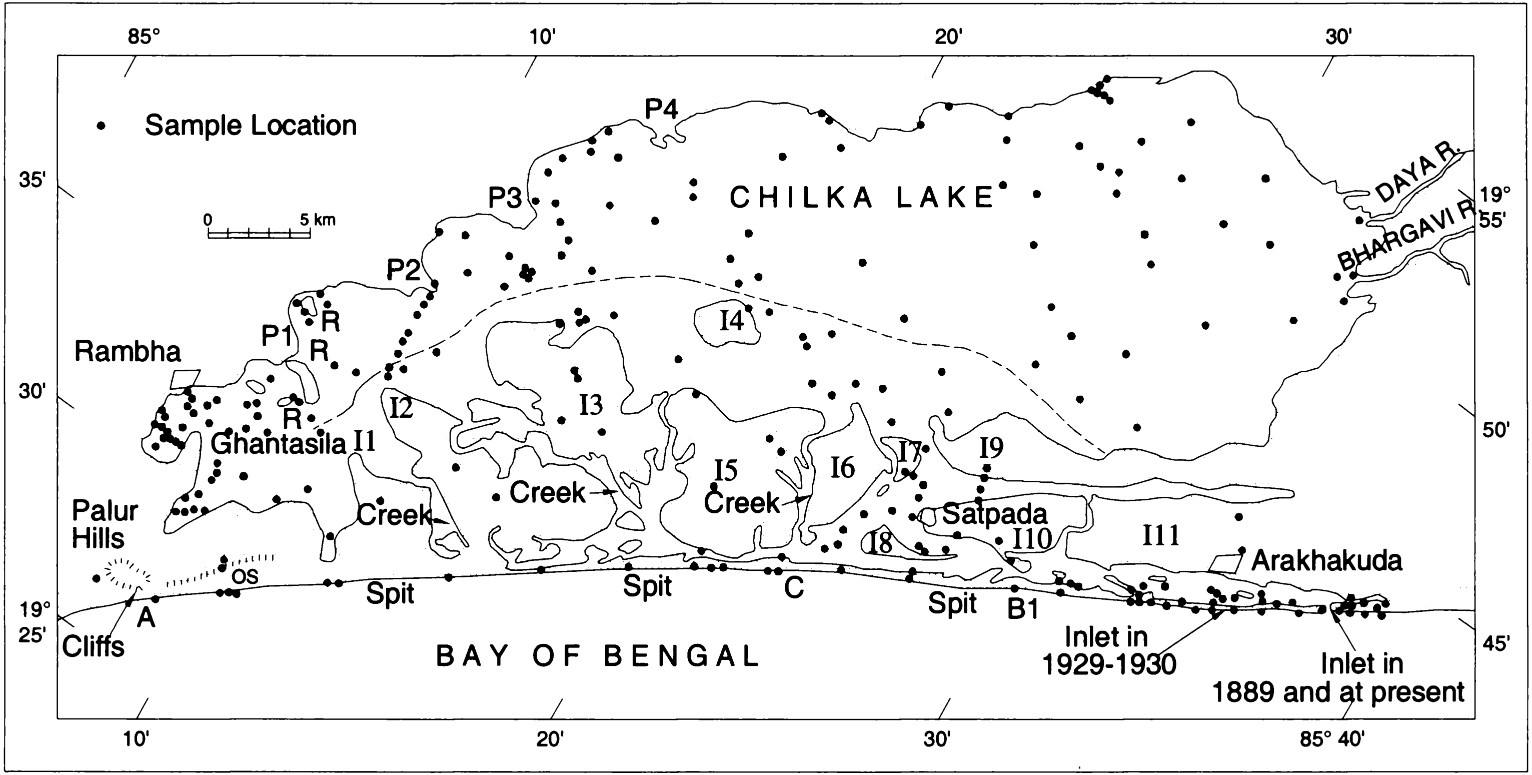

85°
10'
20'
30'
Sample Location
0 5 km
35'
30'
19° 25'
19° 55'
50'
45'
P1
P2
P3
P4
R
R
R
Rambha
Ghantasila
I1
I2
I3
I4
I5
I6
I7
I8
I9
I10
I11
CHILKA LAKE
DAYA R.
BHARGAVI R.
Creek
Creek
Creek
Satpada
Arakhakuda
Palur Hills
OS
A
Cliffs
Spit
Spit
C
Spit
B1
BAY OF BENGAL
Inlet in 1929-1930
Inlet in 1889 and at present
10'
20'
30'
85° 40'

**Fig.1.7.** Certain morphological features of Chilka Lake: I1-I11 = sand ridges adjacent to the spit. P1-P4 = rocky headlands. R = rocky islands. (after Venkatarathnam, 1970, p.103; © 1970; reprinted with permission from Elsevier).

internal drainage. Due to desiccation, deposits of soluble salts are left behind. The source of water in the Sambhar Lake (~30 km long and about 3-8 km wide; 26°55'N: 75°0'E) is mainly atmospheric precipitation, but small ephemeral streams like Roopangarh, Khandel, Kharia and Mendha discharge into it. Almost W-E trending long axis (~22 km) of the lake is parallel to a dextral strike-slip fault zone. There appears to be a causal link between block uplift and lake formation through capture, blockage and ponding of streams. Pokaran saline lake has centripetal drainage. Rows of playa lakes evolve due to segmentation of a stream channel. Didwana, Punlauta and Gonarda lakes are the result of stream strapping in between successive longitudinal dunes. Besides common salt, some of the lakes contain potash and bicarbonates, carbonates and sulphates of various elements.

Kutch Ranns (the Great and Little Ranns) evolved as shallow tectonically subsided areas that allowed transgression of seawater, mainly during the high tides. The Rajasthan Ranns on the other hand are typical inland playa depressions, without having any marine connection.

Chilka Lake along the coast of Orissa (19°28' - 19°54'N and 85°5' - 85°38'E) is a lagoon, separated from the Bay of Bengal by a barrier spit attached at the southern end (Fig.1.7). Landward of the spit, adjacent to it are a number of other sand ridges. Sand for the building of the spit and the other ridges was derived from the sea bed and/or from the land south of Chilka Lake. The processes of deposition of spit and the ridges were initiated sometime during the last sea level rise, before 1.5 million years. There are a number of cuspate spits within the main channel area.

Pulicat Lake (13°25'-13°44'N and 80°02'-80°19'E), along the southern part of Andhra coast, is a lagoon. Its eastern margin is an assemblage of dunes, interdune troughs and older spit heads. The northern margin abuts against an elevated, hard, desiccated palaeo-lagoon bed. The low-lying western margin is occupied by 1-2 m thick coastal ferricretes of late Pleistocene age. The southern margin is a deltaic plain developed by the Old/Proto-Palar river. The surface sediments of the present lagoon are soft silty clay and clay.

Kolleru Lake (16°32'-16°46'N and 81°05'-81°21'E) is a lagoon, which formed between the prograding Godavari and Krishna deltas in the recent past. It was subsequently almost cut off from the sea by successive development of a series of arcuate sand ridges parallel to the coast. It is now separated from the coast by another small lagoon. It has a spread of about 250 km$^2$ during the monsoon. It has now considerably shrunk due to encroachment by reclamation and by artificial silting, partly for agriculture and partly for prawn and fish ponds (pisciculture).

Lonar Lake is located southwest of Lonar town (19°59'N-76°31'21"E) and adjacent to it. Lonar is about 80 km southeast of Buldana in Maharashtra

State. It is a circular depression containing saline water in its central portion. The crater-like landform is 1830 m in diameter and 137 m deep from the highest point on the rim crest, to the water level. Shock ejecta including black glassy material characteristic of intensely shocked basalt are collected here. Mineral maskelynite (known to occur in meteorites and artificially shocked loaded basalts) has been recorded. These seem to indicate a meteor impact origin. This is established on fission-track dating of the shock-melted glass. This impact is considered to have taken place sometime during the last 50,000 years. The youthful characteristics of the crater also support this numerical age. Five basalt flows were mapped inside the lake. These vary from fine-grained at the top to vesicular and/or amygdaloidal unit at the bottom.

Two major lakes along the west coast in Kerala are the Vembanad Lake in the north, almost a lagoon, and Ashtamudi kayal in the south. Both are connected to the Arabian Sea.

### Coastal Features

With a coastline extending over 7500 km, there are numerous landforms resulting from coastal erosion and/or deposition in different stretches of the coast, right from Kutch (also spelt Kachchh) in the extreme west to the Sunderbans in West Bengal in the east. Changes in sea level and tectonics have aided in the preservation and/or loss of some of the coastal features. By and large, depositional landforms are more common along sections of the east coast both in deltas (Fig.13.8) and in the coastal plains (Fig.1.8). Whereas a little in the interior, they are essentially ancient beach ridges, but along the coast they are spits, bars, lagoons, dunes etc. There are, however, a few areas in the east coast where erosional landforms can be met with, where the rocks project into the sea, as in parts of north coastal Andhra Pradesh.

In the west coast also there are many depositional landforms, particularly along Kerala coast, where ancient beach ridges and spits are noted. However, the number of erosional landforms like abrasion platform, wave-cut terrace, sea caves, sea cliffs, headlands, stacks and rocky islands (Fig.1.9) are better developed along certain sections of Maharashtra and Karnataka coasts. Andaman and Nicobar islands in the Bay of Bengal and the Lakshadweep group of islands in the Arabian Sea also show a variety of coastal features. In the former they are mainly erosional and in the latter, mainly depositional, mostly made up of corals. There is a certain amount of mineral potential also in the coastal sediments in the form of mineral sands (beach sands), some of which like those of the Kurda, Orissa and Andhra Pradesh coast containing monazite, rutile, zircon, garnet etc., are being economically exploited.

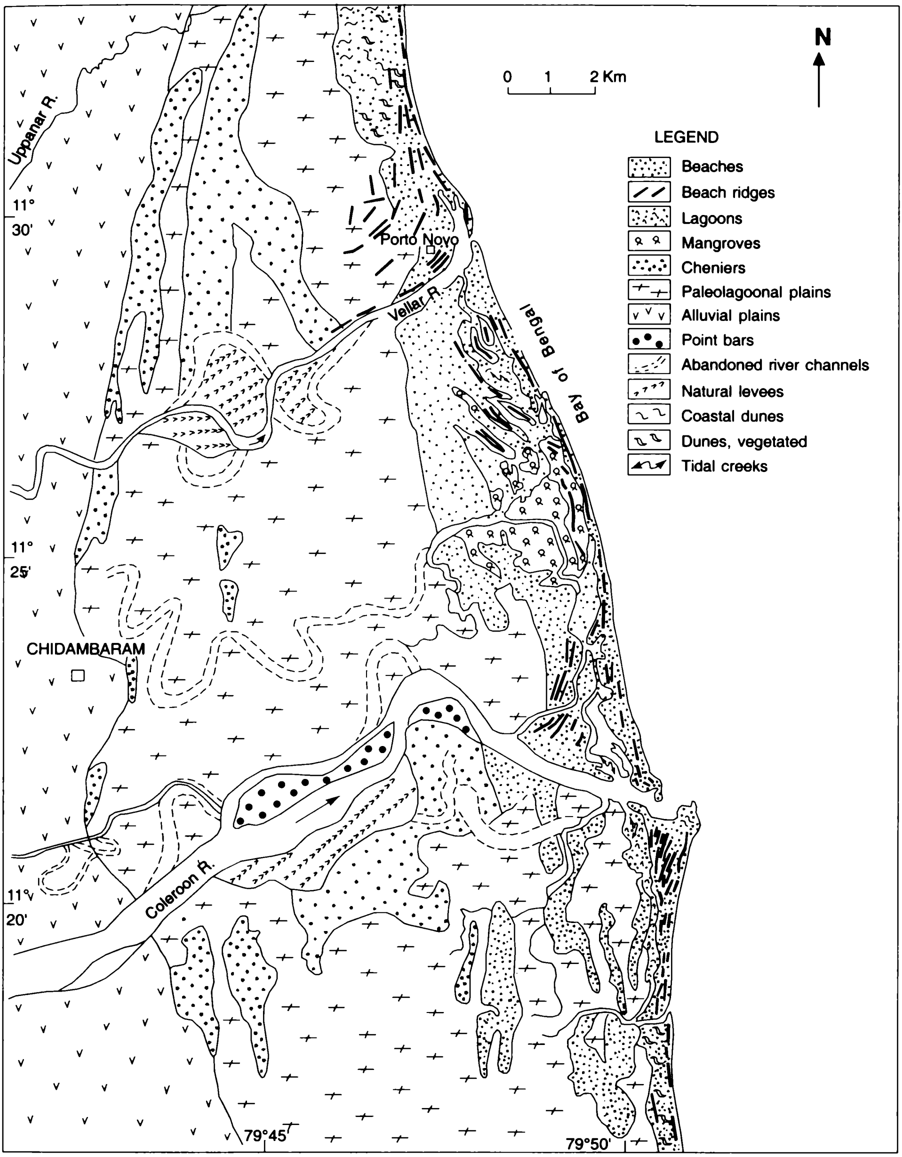

N
0 1 2 Km
LEGEND
Beaches
Beach ridges
Lagoons
Mangroves
Cheniers
Paleolagoonal plains
Alluvial plains
Point bars
Abandoned river channels
Natural levees
Coastal dunes
Dunes, vegetated
Tidal creeks
Uppanar R.
11° 30'
Porto Novo
Vellar R.
Bay of Bengal
11° 25'
CHIDAMBARAM
Coleroon R.
11° 20'
79°45'
79°50'

**Fig.1.8.** Coastal geomorphology around Chidambaram, Tamil Nadu. (after Anbarasu et al. 1999).

## Seas

The Indian Peninsula is surrounded by the Arabian Sea in the west, Bay of Bengal on the east and the Indian Ocean in the south. The advent of Deep Sea Drilling Projects (DSDP) in 1968, now continuing as the Ocean Drilling Program (ODP) has provided ample opportunities for examination of large number of core samples from the tropics to the poles and from the rocks and sediments of Late Mesozoic (~150 Ma) to the present day. They deal with

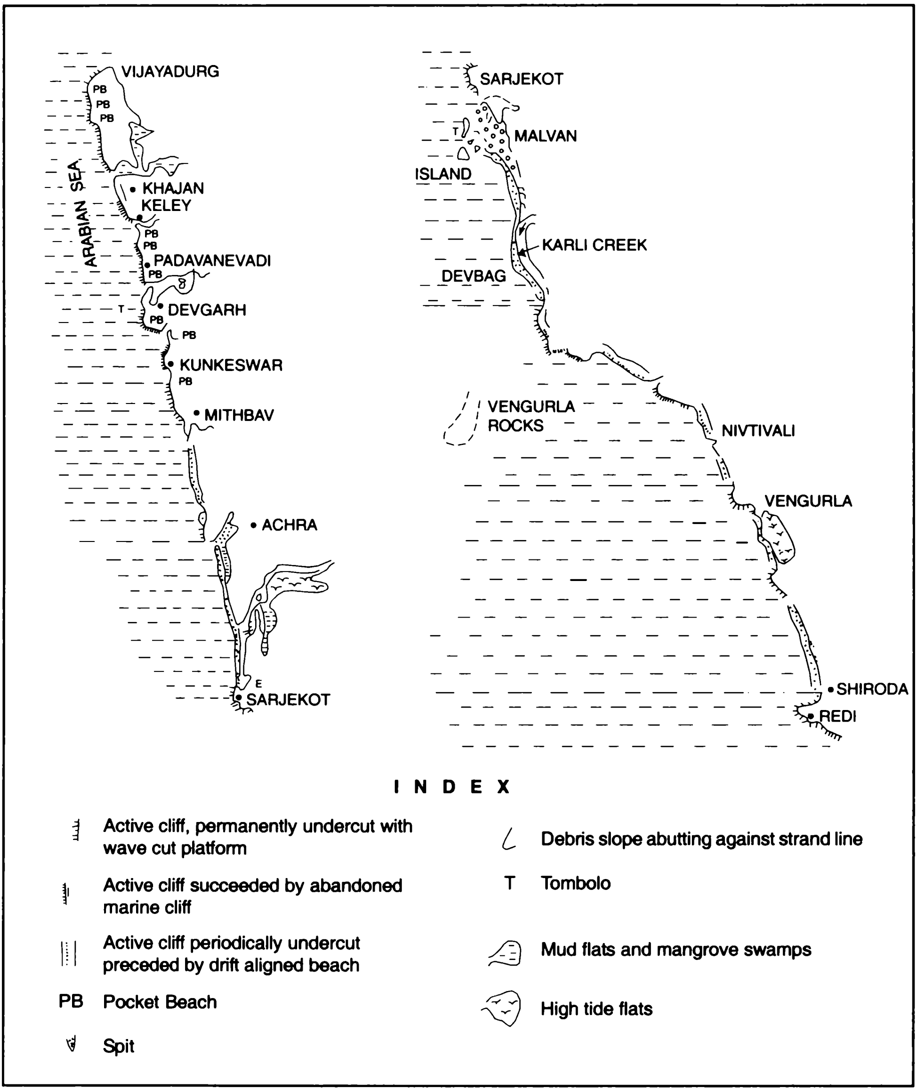

VIJAYADURG
PB
PB
PB
ARABIAN SEA
KHAJAN
KELEY
PB
PB
PADAVANEVADI
PB
T
DEVGARH
PB
PB
KUNKESWAR
PB
MITHBAV
ACHRA
E
SARJEKOT
SARJEKOT
T
MALVAN
ISLAND
KARLI CREEK
DEVBAG
VENGURLA ROCKS
NIVTIVALI
VENGURLA
SHIRODA
REDI
INDEX
Active cliff, permanently undercut with wave cut platform
Active cliff succeeded by abandoned marine cliff
Active cliff periodically undercut preceded by drift aligned beach
PB Pocket Beach
Spit
Debris slope abutting against strand line
T Tombolo
Mud flats and mangrove swamps
High tide flats

**Fig.1.9.** Coastal landforms between Vijayadurg and Redi, Maharashtra (modified after Tiwari and Mallick, 1999, p.219).

surface water palaeoceanography, bottom water palaeoceanography and deep sea hiatuses (breaks in sequence of sedimentation), calcium carbonate record, marine palaeotemperature estimation, impact of weathering on continents and their margins due to oceanographic changes, sea level changes etc.

Bay of Bengal is believed to have formed as a result of collision of the Indian Plate with the Asian Plate. Many major and minor rivers debouch into it carrying a large amount of sediments. The Ganga-Brahmaputra system, drawing from the Himalaya, contributes the maximum amount of sediment, which has led to the growth of the Bengal Fan. The sediments of the Bengal Fan provide an unparalleled record of Himalayan erosion, which in turn, is related to the climate and uplift history of the Himalaya. Bathymetric features of Bay of Bengal are (Fig.1.10) the Bengal Fan, basins, canyons, ridges (aseismic and seismic), subduction zone, plate boundary deformation zone and sea mounts. Of these, the most important is the Bengal Fan, the world's largest delta (though essentially sub-aqueous). The canyons surrounding the Bay of Bengal (Swatch of No Ground, Chilka, Andhra, Mahadevan, Krishnan, Godavari, Gautami, Machili, Nagarjuna, Pennar, Swarnamukhi, Armagaon, Palar, Puducherry, Cuddalore and Trincomalee – the last being off the east coast of Sri Lanka) acted as conduits to supply sediments to the Bay of Bengal. Ninety East Ridge is a prominent physiographic unit extending south to north from the Indian Ocean to close to Andaman Islands. Bay of Bengal represents a super deep sedimentary basin overlying the oldest part of the Indian Ocean lithosphere and contains records of the effect of rifting of Eastern Gondwanaland, passage of the Indian Plate over a mantle plume, accelerated sedimentation due to Asia-India collision and the subduction at the Andaman arc. Dimensions of the Bengal fan: Area – 2.8 to 3.0 X $10^6$ $km^2$; extension – 20°N to 10°S; crustal thickness – 20 km; length – 2800-3000 km; width – 830 to 1430 km; relief features – 800 m; deformed folded features in the subsurface – wavelength 100-300 km. The Indus Fan, which extends from the mouth of Indus river (in Pakistan) down south into the Arabian Sea, has an area of 1.1 X $10^6$ $km^2$, with a length of 1500 km and width of 960 km. The thickness of the sediments ranges from 0.5 km in the distal area to >10 km in the proximal area of the fan.

The width of the continental shelf and the depth at which shelf break occurs are variable. The former ranges in width from 2.5 km off Chennai (Madras) in the east coast of South India to about 210 km off Kolkata (Calcutta), whereas the latter ranges in water depth from around 70 to 240 m. Terraces, pinnacles and ridges occur in the continental shelf at 59, 70, 90 and 101 m and are inferred to be vestiges of palaeostrandlines caused by sea level changes during the Late Pleistocene/Holocene. Palaeochannels have also been reported over the continental shelf.

Arabian Sea has varying widths of shelf and slope. The width of the continental shelf is the maximum, which is about 300 km off north of Mumbai, but it narrows down further south to about 60 km near 10°N. On the other hand the width of the continental slope, which is 135 km off Ratnagiri in the south (around 17°N) tapers down to 65 km off Mumbai in the north (around 19°N). The shelf break occurs generally between water depths of 100 to 150 m and at places, the shelf merges imperceptibly with the upper continental slope. The topography is made up of alternating ridges and depressions (Fig.1.11) of varying magnitude as one proceeds from the coast due west to the Arabian abyssal plain.

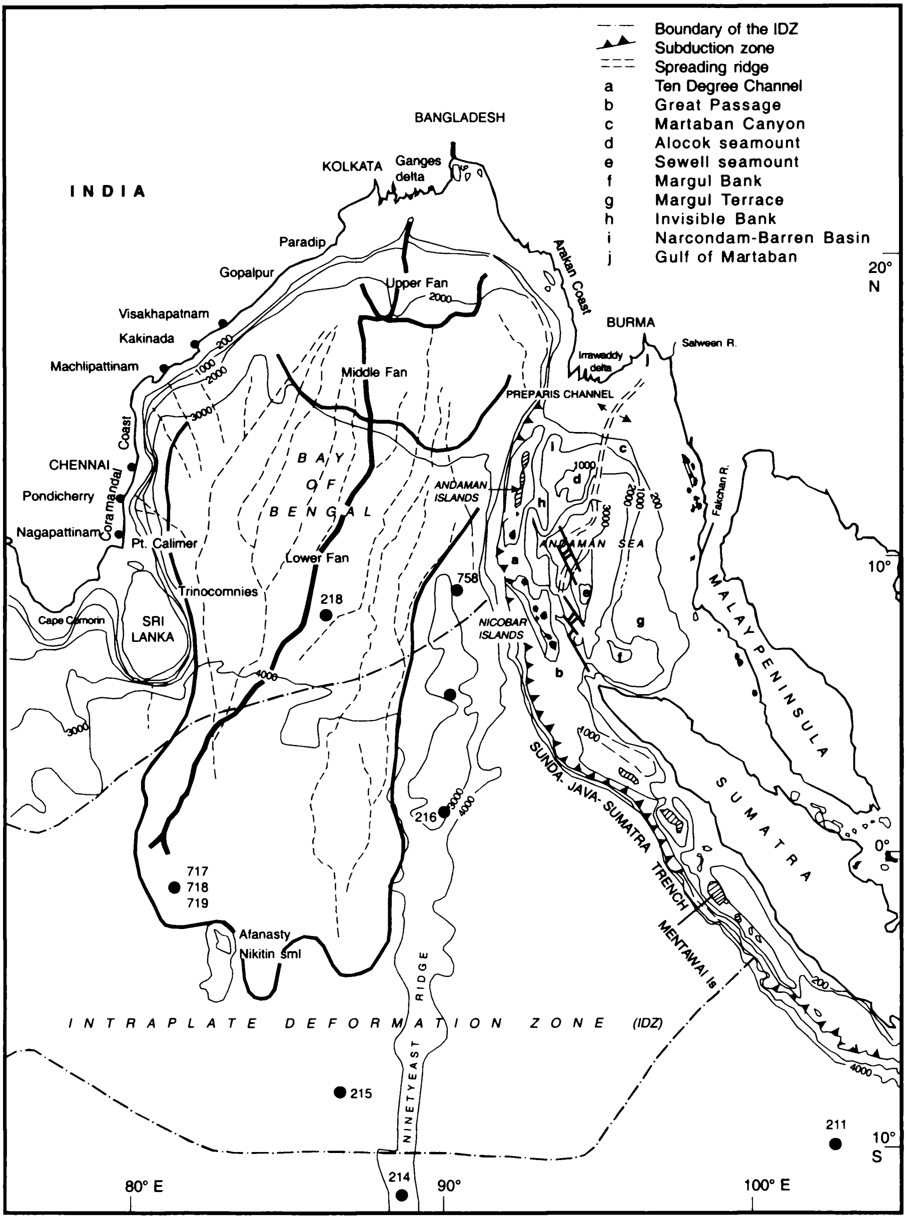

Boundary of the IDZ
Subduction zone
Spreading ridge
a Ten Degree Channel
b Great Passage
c Martaban Canyon
d Alocok seamount
e Sewell seamount
f Margul Bank
g Margul Terrace
h Invisible Bank
i Narcondam-Barren Basin
j Gulf of Martaban
BANGLADESH
INDIA
KOLKATA
Ganges delta
Paradip
Gopalpur
Visakhapatnam
Kakinada
Machlipattinam
CHENNAI
Pondicherry
Nagapattinam
Coramandal Coast
Pt. Calimer
Cape Camorin
SRI LANKA
Trinocomnies
Upper Fan
Middle Fan
Lower Fan
BAY OF BENGAL
ANDAMAN ISLANDS
NICOBAR ISLANDS
ANDAMAN SEA
PREPARIS CHANNEL
BURMA
Arakan Coast
Irrawaddy delta
Salween R.
Falchan R.
MALAY PENINSULA
SUMATRA
SUNDA-JAVA-SUMATRA TRENCH
MENTAWAI Is
NINETYEAST RIDGE
Afanasty Nikitin Sml
INTRAPLATE DEFORMATION ZONE (IDZ)
20° N
10°
0°
10° S
80° E
90°
100° E
717
718
719
218
758
216
215
214
211
200
1000
2000
3000
4000

**Fig.1.10.** Physiographic features of the Bay of Bengal and the Andaman Sea. Thick dark lines across the Bay are the boundaries of the Upper, Middle and Lower Bengal Fan. Thin dashed lines are inferred turbidity currents (source: Purnachandra Rao and Kessarkar, 2001, p.819). (Reprinted with permission from Balkema Publishers).

A series of submarine terraces at depths between 35 and 140 m are reported (Fig.1.12). The most prominent ones have been recognised to occur at depths between 50 and 115 m at six different levels: (1) 55-60 m, (2) 65-70 m, (3) 75-80 m, (4) 85-90 m, (5) 95-100 m and (6) 110-115 m. They are found to be

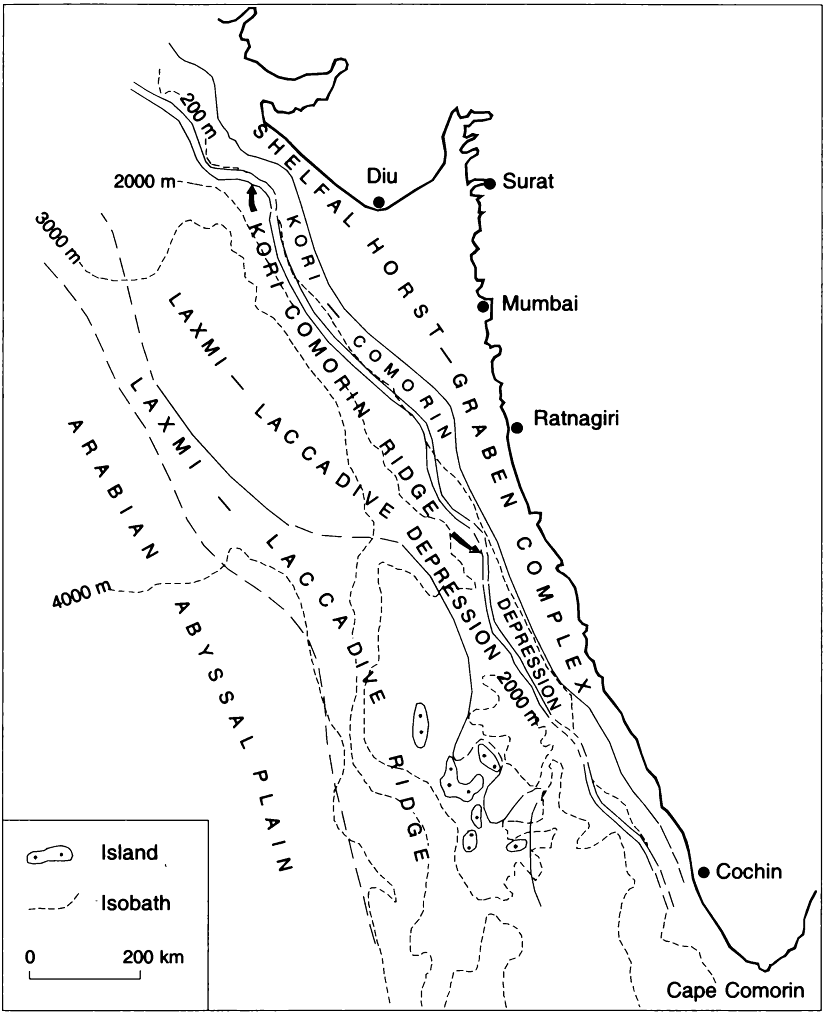

200 m
2000 m
3000 m
4000 m
SHELFAL HORST-GRABEN COMPLEX
KORI
COMORIN
KORI-COMORIN RIDGE
LAXMI - LACCADIVE DEPRESSION
LAXMI - LACCADIVE RIDGE
LAXMI
ARABIAN
ABYSSAL PLAIN
DEPRESSION
2000 m
Diu
Surat
Mumbai
Ratnagiri
Cochin
Cape Comorin
Island
Isobath
0
200 km

**Fig.1.11.** Morphotectonic features of Western Continental margin (source: Radhakrishna and Vaidyanadhan, 1997, p.268).

clearly recognisable between 11°and 20°N, but seem to merge and are less conspicuous further north. The terraces, based on the material collected, are categorised into (a) coral/algal reef induced terraces, and (b) palaeo-beach/barrier terraces and their growth is ascribed to reef growth, progradation and wave activity during low stands of sea level in the late Quaternary.

## Volcanoes

In the Andaman Sea, Barren Island and Narcondam, about 140 km NNE of the former, are known to be extinct volcanoes. However, the sudden eruption on the 28th March 1991 of the former and recently on the 28th May 2005,

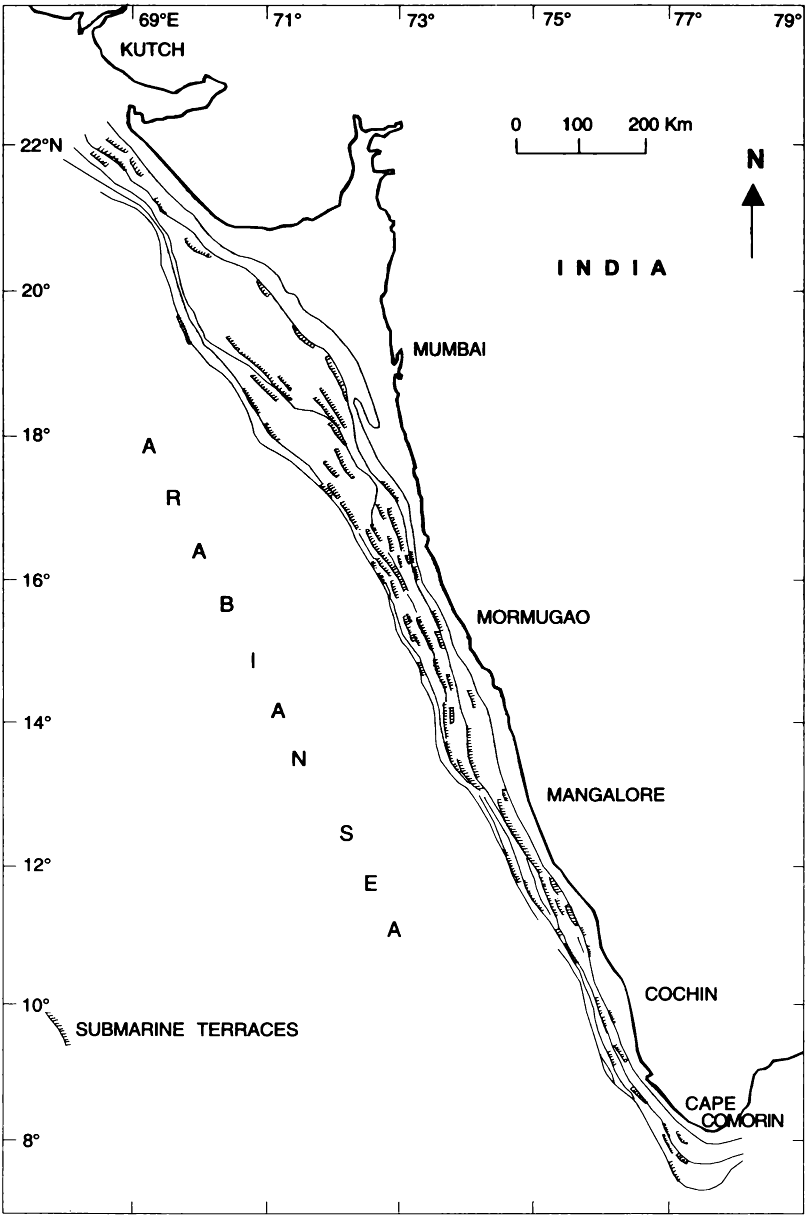

69°E
71°
73°
75°
77°
79°
KUTCH
0 100 200 Km
N
22°N
20°
18°
16°
14°
12°
10°
8°
INDIA
MUMBAI
MORMUGAO
MANGALORE
COCHIN
CAPE COMORIN
ARABIAN SEA
SUBMARINE TERRACES

**Fig.1.12.** Locations of submarine terraces along the western continental shelf and slope of India (after Purnachandra Rao and Wagle, 1997, p.332). (Reprinted with permission from Current Science).

almost after a century and a half, enabled study of this now relatively active volcano. Barren Island consists of a central symmetrical cone with sides sloping at about 35° and with a crater about 13 to 15 m deep. There are a few parasitic cones as well. The volcano was of Stramolian type to start with (moderately fluid magma with cinders, bombs and glassy ash), but later changed to Plinion type (violent ejection of solid rock fragments of lava, viscous magma, with large volumes of ash, followed by caldera collapse).

The earliest flows were olivine basalts, whereas the later ones are olivine bearing basaltic andesites. The chemistry of the Barren Island lavas seems to closely match with that of the island arc tholeiites. The volcanic islands are in a line with similar ones in Myanmar (Burma) in the north and Sumatra in the southeast in a volcanic arc and that these are the results of subduction is indirectly manifested in the presence of an ophiolite zone along the eastern flank of the island chain.

Besides the above there are mud volcanoes as well in Baratang Island distinctly aligned along a prominent north-south trending fault. One of the latest eruptions of mud from this island was on 18th February 2003. Analysis of an earlier eruption of mud from this island indicated the presence of illite, kaolinite, volcanic glass, brine, methane gas, sulphide nodules besides microfossils. The last were essentially mixed coccoliths and foraminifers.

**Seismicity**

Earthquakes occur due to movements along faults that have evolved through geologic and tectonic processes. Earthquakes have been known to occur in India since historical times, but records of the same, partly qualitative and partly quantitative exist since about the 17th century only. These include the year of occurrence, location of the epicentre (latitude and longitude), and magnitude of the earthquake (seismicity, in Richter's scale). Since around 1967 the exact timings of the earthquakes up to the second, together with depth of focus, have also been noted of practically all the earthquakes that took place in the Indian subcontinent. It will be interesting to know that it is the first Director of the Geological Survey of India, Thomas Oldham and later his son R.D. Oldham independently made substantial initial contribution to our knowledge of seismicity in general (regarding the different waves) and Indian earthquakes in particular, during the latter part of the nineteenth century.

Release of the stress developed in a tectonic domain ultimately results in the earthquakes, and fault plane solutions are resorted to as a direct means to study stress conditions in an area. Though recognition of the lineaments or linear geomorphic features can form part of these studies, it is difficult to relate these with any specific seismic activity. Location of epicentres alone may not necessarily provide the fault alignment particularly when the fault planes are inclined and epicentre locations are not sufficiently accurate. Detection of microearthquakes helps in the identification of unknown faults in a region, even though they are not traceable on the surface. The causative faults of recent Indian earthquakes could be well demarcated by precise hypocentral locations of major earthquakes and the after shocks there, by making use of digital monitoring.

In order to understand the focal source and the processes leading to earthquakes, a number of studies have been initiated, which include installation of digital broad-band and short period stations as national network and detailed after shock studies of earthquakes of Magnitude M>6 on the Richter Scale. Techniques such as drilling, helium measurements, magneto-telluric surveys and seismic tomography have widely helped to characterize the seismogenic condition of the lithosphere. Palaeoseismic data help in understanding the long-term behaviour of the faults, generally associated with and inducing earthquakes, a vital parameter required for assessing earthquake hazard. Recently a new dimension has been added in the investigations by initiating Global Positioning System (GPS)-oriented geodetic studies.

The seismotectonic setting of India is distinctive in the two physiographic divisions, viz., (i) seismically active Himalaya, including adjacent northeast India, and (ii) the relatively Stable Continental Region (SCR) of Peninsular India. The seismicity of Himalaya is of interplate type. In the Himalaya, seismicity is causatively related to the three major faults viz., Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Fontal Thrust (HFT) (*see* Fig. 13.9). The SCR seismicity of the peninsular shield, on the other hand, is of intraplate type. Earthquakes occurring at the plate boundaries and plate margins are better understood relative to those within the plates. Though the intraplate continental areas often exhibit geological evidences of neotectonic stability, earthquakes do occur in these areas. Generation of Indian SCR earthquakes is considered to be mainly caused by the continual accumulation of strain energy by a coupled force system, consisting of NNE compression due to movement of the Indian plate and the resultant local tectonic forces. This release of stress is sometimes triggered by reservoir (water)-induced forces or the presence of fluids at the hypocentral depths.

The most intense seismic region in India is the Himalayan Seismic Belt (HSB), which owes its elevation as well as seismicity to the collision tectonics between the Indian and Asian plates along the Indus suture and the subduction tectonics in the NE region and the Indo-Burmese arc in the east. Seismicity is highest within the HSB in the Hindukush region close to the collision zone in the NW and the Assam-Nagaland-Manipur region, close to where the collision zone in the north swings southwards into the subduction zone. In the higher and lesser Himalaya, earthquakes are related to ongoing intraplate deformation. Several earthquakes of M>7 or Intensity >VIII (in the Modified Mercalli Scale) have been reported (Kayal, 2003 and references therein) from both historical records and the more recent instrumental records (Fig.1.13a).

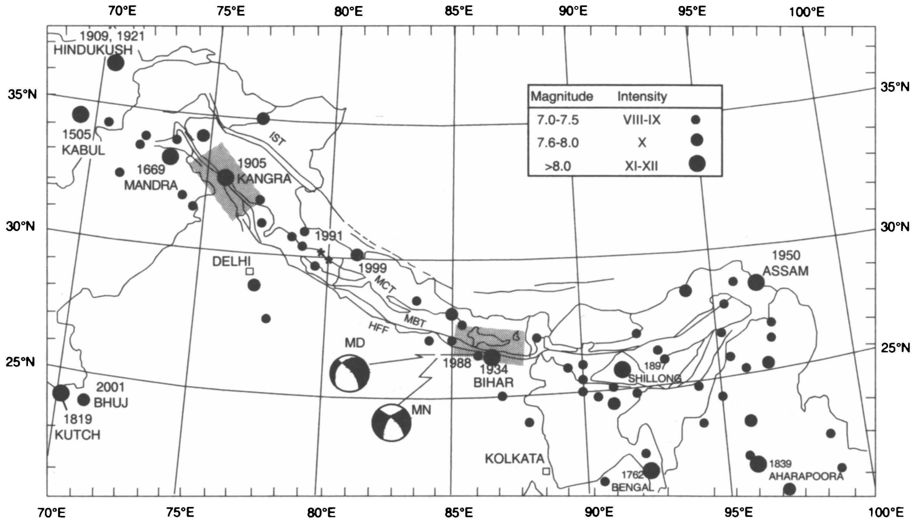
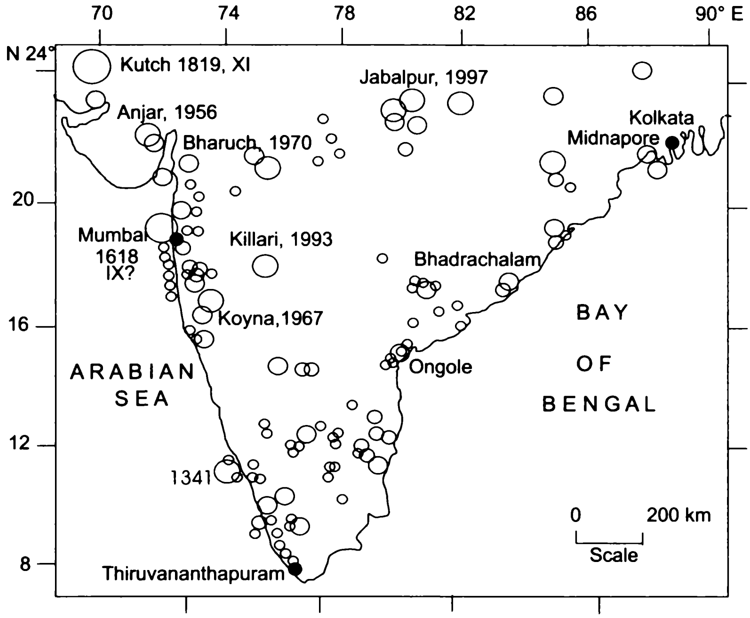

70°E
75°E
80°E
85°E
90°E
95°E
100°E
35°N
30°N
25°N
1909, 1921
HINDUKUSH
1505
KABUL
1669
MANDRA
1905
KANGRA
IST
1991
1999
MCT
MBT
HFF
DELHI
MD
MN
1988
1934
BIHAR
Magnitude
Intensity
7.0-7.5
VIII-IX
7.6-8.0
X
>8.0
XI-XII
1950
ASSAM
1897
SHILLONG
2001
BHUJ
1819
KUTCH
KOLKATA
1762
BENGAL
1839
AHARAPOORA

**Fig.1.13a.** Seismicity map of the Himalaya and surrounding region showing epicentres of the earthquakes of intensity VIII+ and or magnitude 7.0 and above (modified from Chandra, 1992). Epicentres of the three recent damaging earthquakes, 1998 Bihar/Nepal ($M_s$ 6.6), 1991 Uttarkashi ($m_b$ 6.6) and 1999 Chamoli ($m_b$ 6.3) are shown by star symbols. Two fault plane solutions of the 1988 earthquake are shown MN: Moment Tensor solution by NEIC (USGS), MD : Moment Tensor solution by Dziewonski et al. (1989); dark area indicates zone of compression and open area zone of dilatation. The 1819 great Kutch earthquake ($M_L$ 8.4, $M_w$ 7.8) in the western margin of the Indian shield is also shown. In the Himalayan belt the stipples zones indicate rupture areas of the 1905 and 1934 great earthquakes (after Chander, 1989). The meizoseismal area (intensity XII) of the 1897 great earthquake is shown after Oldham (1899) (after Kayal, 2003, p.283).

The effects of the past large Himalayan earthquakes are easily seen in the recently deposited soft fine sediments, which document the signatures of paleoseismicity. Deformation structures and liquefaction are noticed in the soft sediments. The deformed features displayed include over-steepening of the sedimentary strata, folding, graben type faulting, plume-like intrusion, flame structure, slumping and pear drop structures. These are considered to be the products of liquefaction and fluidisation of unconsolidated mud and silt during the historic earthquakes, basically related to the past seismic activity of the MBT or HFT or a blind thrust. The trends of different seismic zones, in general, follow the alignment of tectonic features of the region. The Uttarakashi and Chamoli earthquakes in the Himalaya, for example, are attributed to movements along the pre-existing thrust planes or detachment surfaces due to the underthrusting of the Indian lithosphere. Assam earthquake (1897, M 8.7) is one of those few earthquakes which had caused the largest ruptures (Chedrang fault) of a length >200 km in an east-west direction and width of about 300 km in a north-south direction. Some 'seismic gaps' have been identified: (i) the Kashmir gap west of the 1908 Kangra earthquake, perhaps the recent earthquake of 8th October, 2005 on the Richter scale of 7.6 across western Kashmir and Pakistan is in this gap, (ii) the central gap between the 1905 Kangra and the 1934 Bihar-Nepal earthquake and (iii) the Assam gap between the 1897 Shillong-Assam and the 1950 Assam earthquake. The basis for the identification of seismic gaps is mainly related to the major transverse structural features of the subducting Indian shield. The main governing elements could be the underthrusting rocks. It is postulated that these seismic gaps may be potential candidates for future earthquakes, if the absence of high magnitude earthquakes is due to the continuing slow build up of stresses.

Earthquakes in the Indian Shield share several features of 'Stable Continental Region' (SCR) earthquakes such as Precambrian antiquity and a variable but generally small strain rate shared by several small faults initiated mostly in shallow depths of less than 10 km but rarely traced to depths as high as 30 km. The most dominant fault mechanism is strike-slip though it tends towards thrusting on the one hand and even less frequently into gravity faulting on the other. It is fairly established that most earthquakes in the SCR result by reactivation of earlier faults. The seismo-tectonic provinces of the shield include (i) the Kutch rift basin, (ii) the Cambay and the western pericontinental belt, (iii) the eastern Continental margin, (iv) the interior SONATA-Chhotanagpur belt and (v) the South Indian shield (Fig.1.13b).

The Kutch Peninsula has a long history of earthquakes of varying intensity/ magnitude. The occurrence of the earthquake of 16$^{th}$ June 1819 (M. 7.8) is a unique event of the SCR because of extensive attendant deformation. The 1819 fault scarp, known as "Allah Bund", striking east-west along its northern margin, rises against the salt-encrusted surface for a distance of about 95 km and 16-20 km wide. The one on the 26th January 2001 was also highly destructive. The Broach (Bharuch) earthquake (1970, M. 5.4) occurred near the junction of Narmada, Cambay (Khambhat) and Western Ghat seismogenic zones. The Narmada-Son graben follows an ENE-WSW trend. Earthquakes in the Narmada rift (Jabalpur earthquake, 1997, M. 5.8) seem to occur at very short intervals, and are smaller in size compared to that of Kutch. Focal mechanism solutions of the earthquakes in the Koyna region show strike-slip and normal faulting. The Koyna earthquake of 1967 (M 6.2), one of the most destructive in peninsular India, is considered to be reservoir-induced. The 1989 Idukki earthquake (M 5.7) in Kerala is also considered as an important event in SCR. The Latur earthquake of 1993 (M 6.3) in the central peninsular India is considered to have occurred due to the reactivation of a pre-existing fault. This is an example of a typical mid-cratonic earthquake. It looks as though the region may not have undergone any major rifting since the Precambrian (~570 Ma). South Indian shield witnessed many events epicentred in the Palghat-Cauvery (Pallakad-Kaveri) region, and by the well-known 1900 Coimbatore


70
74
78
82
86
90° E
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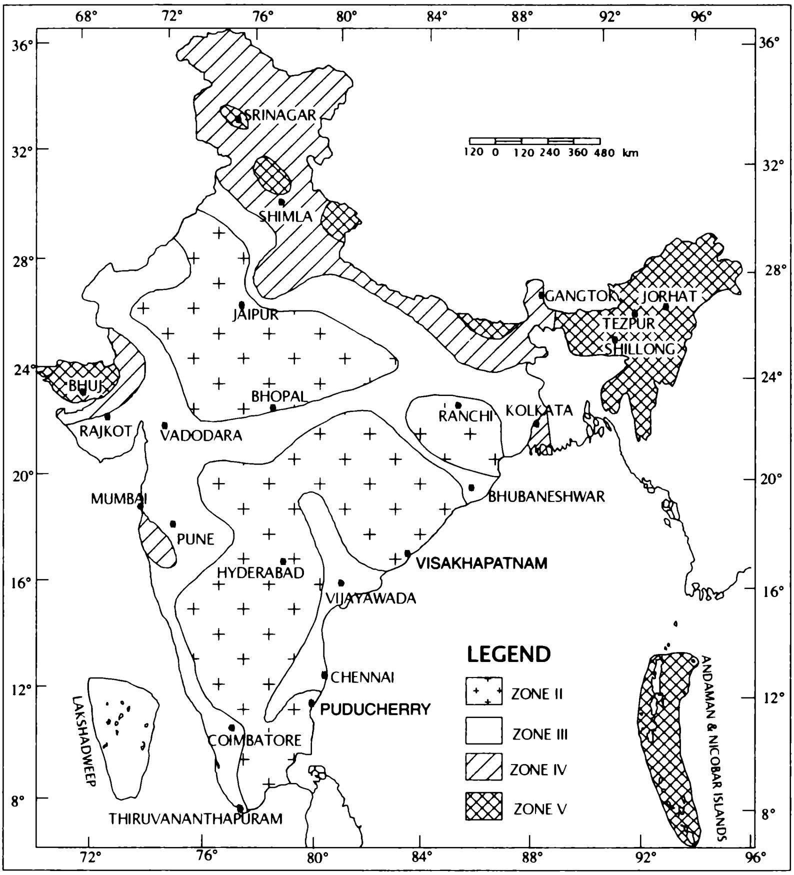
20
16
12
8
Kutch 1819, XI
Anjar, 1956
Bharuch, 1970
Jabalpur, 1997
Kolkata
Midnapore
Mumbai
1618
IX?
Killari, 1993
Bhadrachalam
Koyna,1967
ARABIAN
SEA
BAY
OF
BENGAL
Ongole
1341
Thiruvananthapuram
0
200 km
Scale

**Fig.1.13b.** Seismicity of Peninsular India from historical (AD 12th Century) to recent times. Circles indicating magnitudes are scaled to size; earthqukes at Koyna and Killari are of magnitude >6.0 and those at Bhadrachalam are >5.0 and so on (after Rajendran and Rajendran, 2000, p.1253). (Reprinted with permission from Current Science).

(? M- 5.5/6.4) and Dharmapuri rift systems, exemplified by Shevroy-Salem events. Several moderate to sub-moderate events have been recorded along the eastern continental margin and include the 1867 Villupuram, the 1859/1984 Tiruppathur, 1966 Tambaram, 1967 Ongole (M-5.4) and 1969 Bhadrachalam (M-5.7) events. To these must be added the tsunamis of the 26th December, 2004, resulting from a subaqueous earthquake, far off in Sumatra, but seriously affecting sections of the Indian coast.

*Seismic hazard and risks:* Among all the natural calamities, earthquakes are the most disastrous since their impact leads to deaths, injuries and destruction over vast areas. The extent of impact of an earthquake depends on its magnitude, location and time of occurrence.

Efforts have been made in India by the Bureau of Indian Standards to generate Indian Standard for earthquake resistant design for structures (IS 1893, Part 1, 2002). The Indian region has been broadly divided into 4 seismic zones estimating the probable maximum known earthquake damage in the Modified Mercalli (MM) scale, the lowest zone II registering events of an intensity VI and less and the highest zone V registering intensities of IX or more (Fig. 1.13c). This is a broad categorisation based on probability and does not rule out remote possibilities of earthquakes in a zone of higher intensities than the values used for graduating the scale. Generally those above 5 in Richter's scale can cause damage. Now-a-days many strategies are being evolved to minimise the adverse effects of the earthquakes through proper seismic hazard evaluation, appropriate building codes and also creation of public awareness, besides upgradation of seismological instrumentation network practice.


68°
72°
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84°
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32°
28°
24°
20°
16°
12°
8°
120 0 120 240 360 480 km
SRINAGAR
SHIMLA
JAIPUR
BHOPAL
BHUJ
RAJKOT
VADODARA
MUMBAI
PUNE
HYDERABAD
VIJAYAWADA
VISAKHAPATNAM
BHUBANESHWAR
RANCHI
KOLKATA
GANGTOK
JORHAT
TEZPUR
SHILLONG
CHENNAI
PUDUCHERRY
COIMBATORE
THIRUVANANTHAPURAM
LAKSHADWEEP
ANDAMAN & NICOBAR ISLANDS
LEGEND
ZONE II
ZONE III
ZONE IV
ZONE V

**Fig.1.13c.** Map of India showing four seismic zones (IS 1893, part 1, 2002; reprinted with permission from Bureau of Indian Standards).

Each zone denotes intensity of damage caused by earthquakes. This is expressed in the Modified Mercalli (MM) scale.

| | | | |
|---|---|---|---|
| Seismic Zone | II* | Intensity | VI and less |
| | III | | VII |
| | IV | | VIII |
| | V | | IX and above |

*The earlier map of Seismic Zones of India (ISI, 1986) included five seismic zones (I to V) of which zone I denoted intensities III and below, while zone II denoted intensities of IV, V and VI. However, in the revised edition (BIS, 2002; see Fig. 1.13c) with only four zones, the earlier ISI zone I is now included in the BIS zone II. This has been done in order not to disturb the intensity ranges already given for the later zones of III, IV and V.

## CLIMATE

With the country spanning across a latitudinal spread of about 28° and longitudinal span of about 30° in the northern hemisphere, regions of very high (Himalaya), medium (Western and Eastern Ghats) and low relief (Ganga Plains, coastal plains and the Thar Desert), and surrounded by seas on three sides, India presents a complex terrain. The climate, in terms of precipitation and temperature (omitting other parameters) has wide variation in the different periods of the year influenced by monsoonic winds and ocean currents. It is also influenced by the Himalayan Mountain in the north, which practically shields the whole country from the cold winds of Central Asia, and in the south the Indian Ocean gives it a hot monsoon climate. The climate of India can be described as tropical monsoon type and it is marked by distinct winter and summer seasons.

The term 'monsoon' owes its origin to the Arabic word 'mausam,' which simply means 'season.' In fact, monsoons are seasonal winds whose direction more or less reverses twice during the year. During the winter third of the year (October-January), the general flow of the dry continental air is from north to south and east, and, in the southern part of the Peninsular India and the neighbouring seas, towards northwest. The season is known as Northeast or Winter monsoon. In the southwest monsoon or summer monsoon season during June-September, the winds, which are maritime and moist in great depth, move southwesterly over Bay of Bengal and Arabian Sea. The southwest monsoon enters India in two main branches, the Arabian Sea current and the Bay of Bengal current. The former strikes the west coast to give heavy rain on the windward side of the Western Ghats (*Sahyadri*). The southern part of Arabian Sea current, after crossing over the Sahyadri Ranges blows across the Peninsula as a west or northwesterly wind giving occasional heavy thundershowers. The northern part of this current crosses the Saurashtra coast, blows across Rajasthan up to Punjab and Himachal Pradesh as a southwest wind and gives rain in the coastal districts of Gujarat, near the Aravalli Hills of Rajasthan and Punjab-Kumaon Hills. The Bay of Bengal current crosses the Myanmar coast and extends as a southerly stream up the Irrawady valley and across Arakan Yoma Mountains. A part of this current which crosses Bengal coast and which strikes Jaintia, Khasi and Garo Hills gives copious rain near these hills and in the southern parts of Bengal. The Bay of Bengal current is eventually deflected by the mountains westwards to reach north Bengal and up the Gangetic plain. The country receives about 85% of its rainfall during the southwest monsoon season.

In Western India, the Arabian Sea current confronts the Western Ghats (*Sahyadri* Mountains), which rises precipitously across to an average height of

1200 m. The result is orographic rainfall, being heavy (>250 cm) all along the west coast. The lee side towards the east receives less than 100 cm of rainfall and is typically rain-shadowed. Droughts are very frequent in the region east of the Ghats, particularly in upland Maharashtra and northern Karnataka. Further north in Gujarat and Western Rajasthan (Thar), the Arabian Sea monsoon currents are not able to cause precipitation as hot and dry upper air from Baluchistan (in Pakistan) penetrates the area and checks upward movement and condensation. Thus the whole of Thar Desert between Aravalli and Kathiawar Plateau (Saurashtra in Gujarat) receives a low annual rainfall varying between 25 and 100 cm.

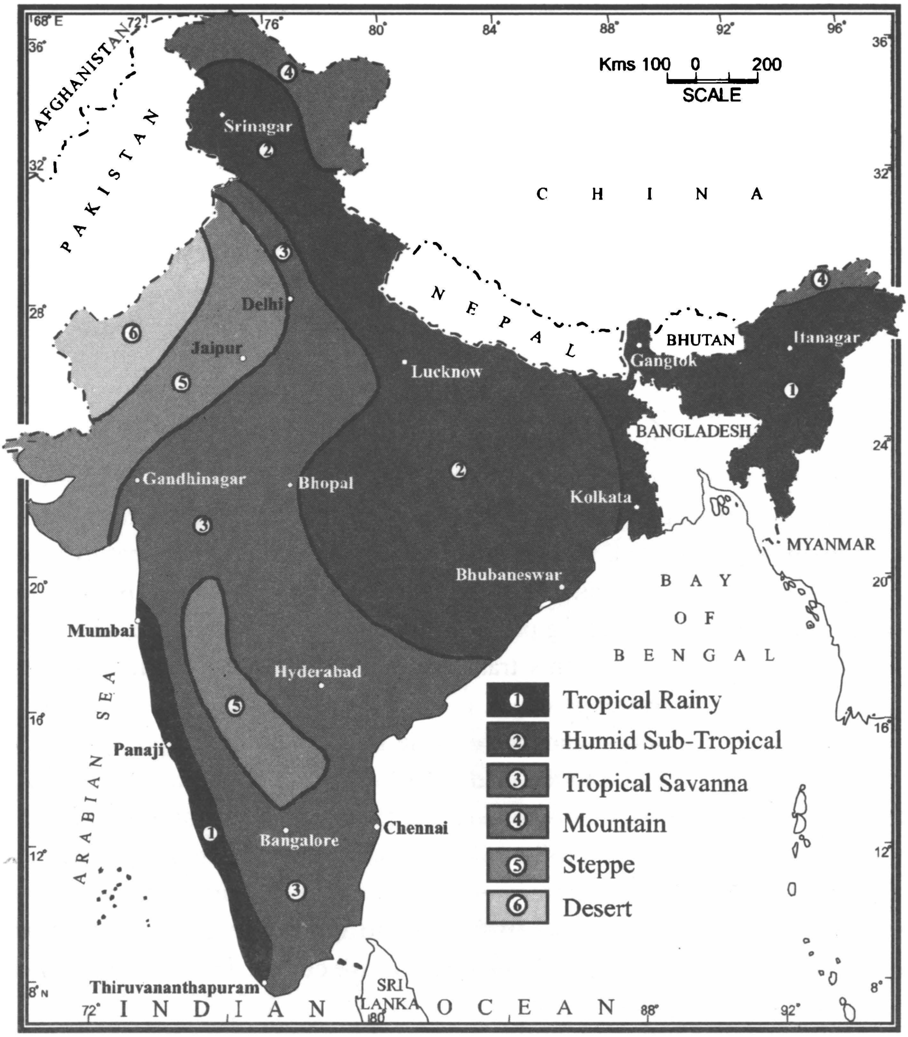
The complexity of the relief features as well as the differential effects of weather systems in different regions are responsible for a variety of climatic patterns observed in the Himalaya. It acts as a massive barrier to the north of the country stretching over a length of about 2500 km. The summer monsoon (June to September) current penetrates into the southeastern parts through the deeply entrenched valleys and sheds precipitation over these areas. Towards eastern Himalaya, the annual rainfall may go up to 400 cm, but in the west it is less than 200 cm. By forcing horizontally moving air to ascend, the mountains increase the cloudiness and precipitation on their windward slopes. The precipitation increases up to 225 cm up to a height of 2.5 km, above which it decreases down to 90 cm owing to the decreasing moisture content of the air. Compared to those on the southern slopes, where the monsoon rainfall may go up to about 200 cm, the precipitation on the northern slopes can be said to be negligible and may be of the order of 10 cm or even less. A major part of India starting from Kerala, coastal Karnataka and Maharashtra, through Andhra Pradesh, Orissa, West Bengal, Assam, northeastern states, Gangetic Plains, central and western India receive rains during the summer monsoon (June to September), also called southwest monsoon. However, Tamil Nadu receives rainfall during the months of October to December, during the northeast monsoon (also called retreating monsoon). Cyclonic storms usually occur during the months of October and November in the Bay of Bengal, which not only bring copious rainfall to parts of the States along the East Coast but also sometimes cause destruction of life and property, if sufficient precautions are not taken.

The average annual rainfall for India, as a whole is around 120 cm, which is apparently satisfactory. There are variations from this normal as great as +30 to –20, which sometimes result in floods and droughts respectively. The normal annual rainfall varies from about 400 cm to less than 20 cm in different parts of the country. Very high precipitation of the order of over 800 cm during southwest monsoon is experienced on the southern slopes of Khasi and Jaintia Hills of Meghalaya, the southern slopes of

Assam Himalaya (Cheerapunji - 1143 cm) and western slopes of the Western Ghats. Very low precipitation is experienced (less than 40 cm) in Saurashtra, western Rajasthan and northern Kashmir.

As for the temperature, the coldest months are usually from December to February, being severe in Punjab and Gangetic Plains, going down even to -5°C. But during March to July the temperature slowly rises even up to 48°C, in the interior parts.

Figure 1.14 gives a very generalised picture of the climate of India in the categories listed therein. From this it can be clearly seen that the climate of India is basically tropical in character.


Kms 100 0 200
SCALE
AFGHANISTAN
PAKISTAN
CHINA
NEPAL
BHUTAN
BANGLADESH
MYANMAR
BAY OF BENGAL
ARABIAN SEA
INDIAN OCEAN
SRI LANKA
Srinagar
Delhi
Jaipur
Lucknow
Gangtok
Itanagar
Gandhinagar
Bhopal
Kolkata
Bhubaneswar
Mumbai
Hyderabad
Panaji
Chennai
Bangalore
Thiruvananthapuram
① Tropical Rainy
② Humid Sub-Tropical
③ Tropical Savanna
④ Mountain
⑤ Steppe
⑥ Desert
68° E
72°
76°
80°
84°
88°
92°
96°
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32°
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24°
20°
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8° N

**Fig.1.14.** Climatic regions. (source: National Atlas and Thematic Mapping Organisation, 1999).

*Tropical Rainy*: Consistently high temperature, April and May being hottest; July and August are the wettest months.

*Humid Subtropical*: Maximum temperature during summer months goes up to 48°C; rainfall mostly in summer monsoon and winters are dry.

*Tropical Savanna*: Long dry period; maximum temperature may go up to 48°C. Rain generally in summer months with Tamil Nadu getting the rains in the winter.

*Mountain*: Covers the Himalaya; cold winter months (November to January), scanty rainfall on the northern slopes; western/southern slopes receive heavy rainfall.

*Steppe:* Low rainfall during southwest monsoon (July to September); average temperature over 27°C, occasionally rising up to 48°C during summer.

*Desert*: Temperature in summer goes up to 48°C, while it goes down even to zero in winter months. May and June are the hottest months. Very unreliable rainfall.

## SOILS

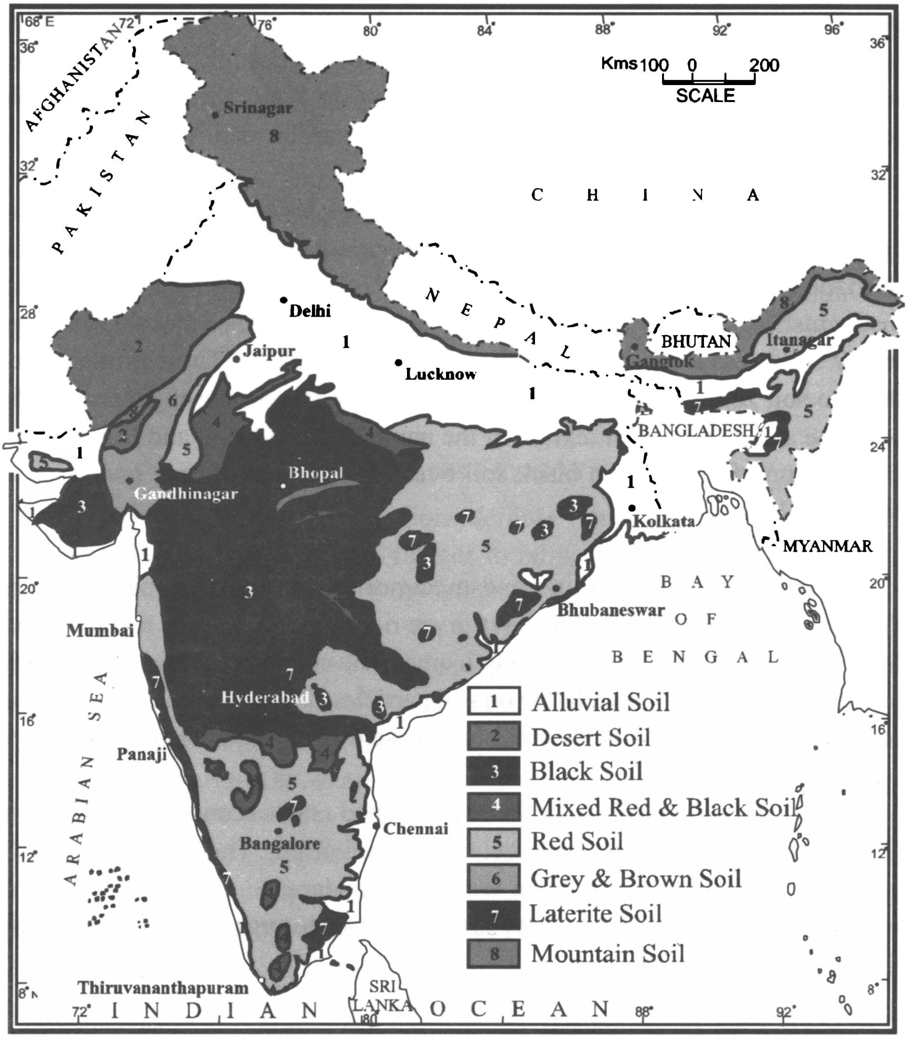
It is well known that the formation of soil is controlled to different degrees, by the following passive conditions of (i) parent material, (ii) landform and (iii) time, and active agents of (iv) climate and (v) biological activity. India with many types of rock formations, with conspicuous relief features and variations in climate is found to contain different types of soils. Soils form due to alteration of rock over a long period of time resulting in a profile (*in situ*) or they can be found in sediments transported and deposited, brought in by a transporting agency (water or wind).

Though earlier soil studies were made from a geological point of view, later emphasis was shifted to the study of profiles and chemical composition. This was found necessary in order to meet the needs of the agriculturist, the main user of the soil. A soil profile starting from unaltered parent material rock (D) at the bottom passes up to weathered /altered rock (C), then to a transitional zone (illuviation) of a dark colour (B) and then to a zone of leaching (alluviation) and decomposed organic matter (A), light to dark colour. The true soil is A+B part of the profile called "Solum".

To start with, soils in India were divided into 5 major soil regions (Red Soil, Black Soil, Alluvial Soil, Desert Soil and Mountain Soil) and then into about 24 Soil Groups. Maps prepared depicted these, depending upon the permissible limit of the scale and dependability of the data collected from the field and the laboratory.

In Figure 1.15 is presented generalised picture of the distribution of the major soils. Their main characteristics are as follows:

*Alluvium*: Most of them are transported essentially by water. They are generally of silty nature with immature profile. They are very productive. Those in the deltas can be clayey, whereas those along the coast a little sandy. In the case of the Gangetic Plain, patches of saline alkaline soils are also met with.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Kms 100 0 200
SCALE
AFGHANISTAN
PAKISTAN
CHINA
NEPAL
BHUTAN
BANGLADESH
MYANMAR
SRI LANKA
Srinagar
Delhi
Jaipur
Lucknow
Gangtok
Itanagar
Bhopal
Gandhinagar
Kolkata
Bhubaneswar
Mumbai
Hyderabad
Panaji
Chennai
Bangalore
Thiruvananthapuram
ARABIAN SEA
BAY OF BENGAL
INDIAN OCEAN
1 Alluvial Soil
2 Desert Soil
3 Black Soil
4 Mixed Red & Black Soil
5 Red Soil
6 Grey & Brown Soil
7 Laterite Soil
8 Mountain Soil

**Fig.1.15.** Soils. (source: National Atlas and Thematic Mapping Organisation (NATMO); Indian Council of Agriculatural Research (ICAR) and other government publications).

*Desert Soil*: These are confined to western Rajasthan and southern parts of Punjab and Haryana where the annual rainfall is less than 50 cm. These are either skeletal soil made up of unassorted material or just sandy. The pH is on the alkaline side. Though the calcium content of the soil is high, the phosphates together with nitrates make them fertile enough for some agricultural crops.

*Black Soil*: These are also referred to as regur soil rich in clay. It is not only over the Deccan Trap country, but also extends over certain parts of northern Karnataka (Raichur doab), Andhra Pradesh and Tamil Nadu. The most characteristic black soil occurs in low-lying areas or depressions in Deccan, though it can be observed in certain plains in other areas. They have a high coefficient of expansion and contraction. In the genesis of black soils the presence of high proportion of alkaline earths in the weathering complex is considered to be of great importance. These occur generally only in climates with pronounced dry seasons extending over 4 to 8 months. In Tamil Nadu some of these are considered to have resulted from lacustrine sediments.

*Mixed Red and Black Soil*: In the surface layers, the black soils are generally mapped as clays, but with the decrease in the thickness of solum (horizons A+B), the textures of clay loam, loam and sandy loam are also distinguished. Similarly the red soils over large areas are breakable into red loamy soils, less leached, red sandy soil, lateritic soil etc. These groupings of the two soil zones of the Peninsular region bring about inter-digitation of the soil type and also the soil texture in the name of Mixed Red and Black Soils. The mix up of the red and black soil over long periods of time gives rise to brown soils.

*Red Soil*: The crystalline and metamorphic rocks of a major part of Peninsular India, on weathering have given rise to red soils. The texture varies from sand to clay, the majority being loams. The colour is mainly due to ferric oxides occurring as a thin coating on soil particles. The soils are either shallow or deep. The characteristic clay mineral present is of kaolinite type.

*Grey and Brown Soil*: These are developed under semiarid conditions in Gujarat and Rajasthan and are largely of alluvial origin. The texture of the soil is usually light being sandy loam with a preponderance of coarse sand. The soils are neutral or alkaline. They are deep, poor in organic matter but fairly rich in potash and phosphorous.

*Laterite Soil*: Though laterites form caps on plateau tops, lateritic soils are usually thin, rarely having a profile of more than 60 to 90 cm. The soils are freely drained and occur on gently sloping terrain. They have a low moisture retentivity and are occasionally subject to severe surface erosion. The soils are denuded of exchangeable bases. The silicate and alumina ratio is low. The soils are generally of a loamy texture. They do have humus in the shallow layer, but if the natural vegetation is removed, humus content in the soils gets depleted and regeneration of plant life becomes difficult.

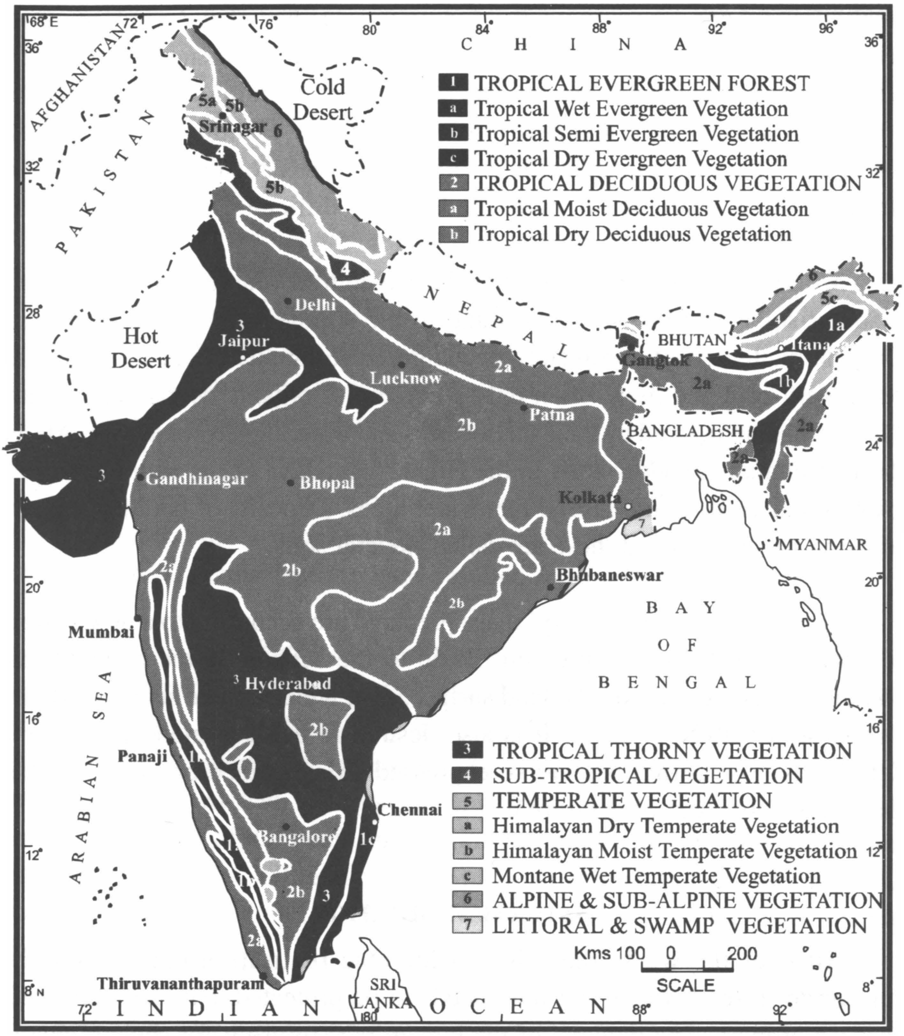
*Mountain Soil*: These are thin dark coloured (darker when wet) and granular soils with brown spots found in the Alpine zone of the Himalaya. Organic matter is not completely decomposed to humus because of the area being very cold and more often only a horizon of organic debris is met with. The profiles are marked by their shallowness and waterlogged conditions. Above these, mountain meadow soils in the Higher Himalaya occur with unassorted gravels and sands in the glacial meltwater areas. Deposits of boulder clay are found in these areas and these are called skeletal soils.

In recent years detailed soil maps prepared are according to a new system scheme called 7th Approximation. Basic to the scheme is the concept that comprises a continuum on the land surface, one, which can be subdivided into classes in a variety of ways. It is also desired to achieve more quantitative definitions. The definitions are so expressed so as to incorporate properties that can be observed or measured.

## NATURAL VEGETATION

All over the world there is considerable realisation that the natural vegetation (forest) wealth not only needs to be protected, but also increased, because of increasing demand of the human race to use it for shelter, energy and food. This endeavour leads imperceptibly for the betterment of the environment and to the welfare of human and animal life in the long run. The distribution of natural vegetation or forest is closely related to the distribution of rainfall, nature of topography and geographical location of the region.

In India 7,43,534 $km^2$ of area is under forests. Most of the forests contain broad-leaved deciduous trees (85%). Teak and *sal* are among the important constituents of these. Coniferous forests occur mainly in the Himalaya between 2150 and 3850 m. The major trees are pines, junifers and *deodars*. Though it is desired to have a forest cover of at least 33 per cent, the actual area is around 22 per cent. Estimates of actual cover, by different agencies, differ but that helps in clearer understanding of the problem. Figure 1.16 is a simplified natural vegetation map of India indicating distribution of the major types of vegetation.


C H I N A
TROPICAL EVERGREEN FOREST
a Tropical Wet Evergreen Vegetation
b Tropical Semi Evergreen Vegetation
c Tropical Dry Evergreen Vegetation
2 TROPICAL DECIDUOUS VEGETATION
a Tropical Moist Deciduous Vegetation
b Tropical Dry Deciduous Vegetation
3 TROPICAL THORNY VEGETATION
4 SUB-TROPICAL VEGETATION
5 TEMPERATE VEGETATION
a Himalayan Dry Temperate Vegetation
b Himalayan Moist Temperate Vegetation
c Montane Wet Temperate Vegetation
6 ALPINE & SUB-ALPINE VEGETATION
7 LITTORAL & SWAMP VEGETATION
Kms 100 0 200
SCALE
AFGHANISTAN
PAKISTAN
Cold Desert
Hot Desert
Srinagar
Delhi
Jaipur
Lucknow
Patna
NEPAL
BHUTAN
Gangtok
Itanagar
BANGLADESH
MYANMAR
Gandhinagar
Bhopal
Kolkata
Bhubaneswar
BAY OF BENGAL
Mumbai
ARABIAN SEA
Hyderabad
Panaji
Chennai
Bangalore
Thiruvananthapuram
SRI LANKA
INDIAN OCEAN
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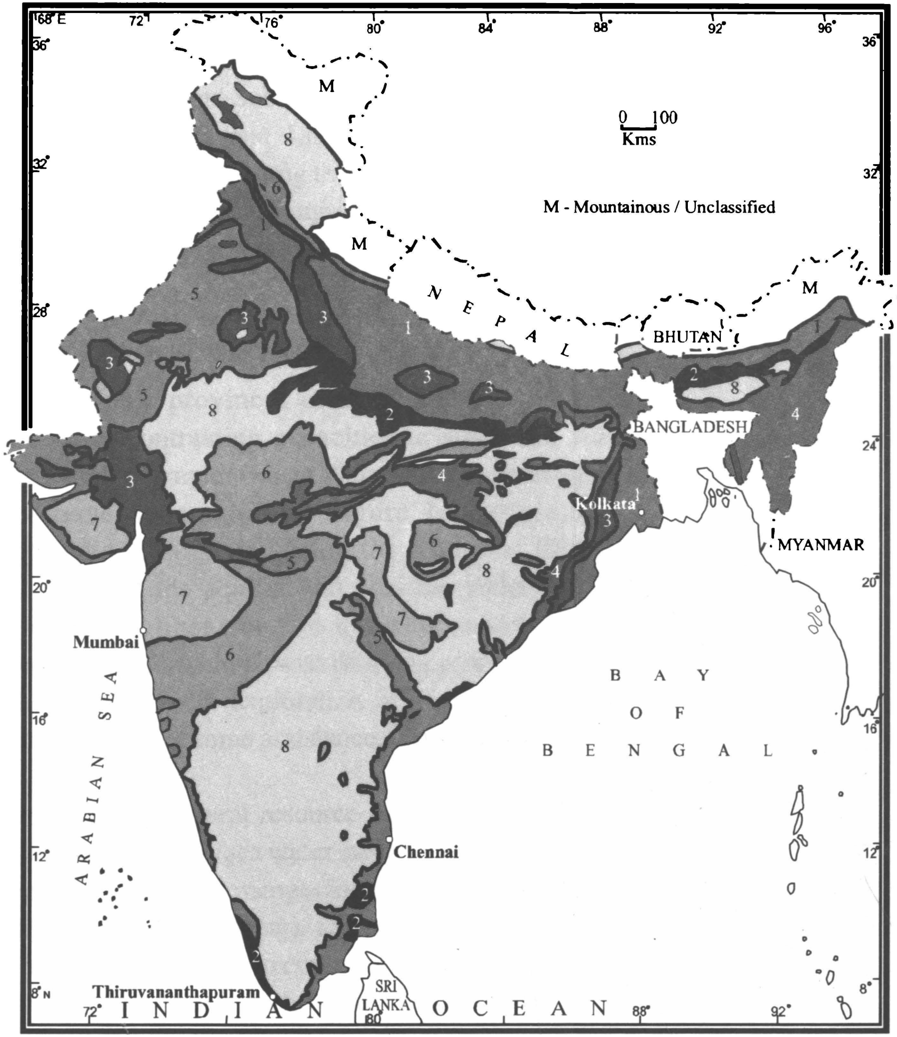
96°
36°
32°
28°
24°
20°
16°
12°
8°N
8°
1a
1b
1c
2a
2b
3
4
5a
5b
5c
6
7

**Fig.1.16.** Natural vegetation. (source: National Atlas and Thematic Mapping Organisation (NATMO), 1999; Indian Forest Statistical Reports, Forest Survey of India and other government agencies).

Certain climatic regimes, such as the tropical wet-dry regime (including monsoon climates, as prevalent in India) and the continental regime, where it is moist but not too cold, are found to have an yearly cycle. During this period water is not available to plants, because of lack of precipitation or because soil water is frozen. This season alternates with the one during which plentiful water is available for the plant. Those trees and shrubs that cannot thrive without water and shed their leaves are deciduous and those that can thrive throughout the year are evergreens.

Tropical evergreen forests with certain variations in them are found mainly along the west coast of India and in parts of northeastern states, mainly because



1 Unconsolidated Formations--Quaternary--Recent Alluvium, Clay, Silt, Gravel, Pebble, Calcareous Concretions--Fairly thick and regionally extensive confined/unconfined aquifers down to 300 m--Large Ground Water yield prospects above 150 m$^3$/hr

2 Unconsolidated Formations--Upper Tertiary--Older Alluvium & Laterite, Silt, Sand, Ferruginous Concretions, Lithomargin Clay, Gravel, Pebbles, Cobbles etc.-- Fairly thick but discontinuous confined/unconfined aquifers down to 300 m--Large Ground Water yield prospects above 150 m$^3$/hr

3 Semi-consolidated Formations--Tertiary, Mesozoic, Upper Palaeozoic--Siltstone, Claystone, Grit, Sandstone, Shale, Conglomerate, Limestone, including intrusives (Andaman)--Moderately thick and regionally extensive confined/unconfined aquifers downto 150 m--Moderate Ground Water yield prospects 50 to 150 m$^3$/hr

4 Semi-consolidated Formations--Tertiary, Mesozoic,Upper Palaeozoic--Siltstone, Claystone, Grit, Sandstone, Shale, Conglomerate, Limestone, including intrusives (Andaman)--Moderately thick but discontinuous confined/unconfined aquifers--Moderate Ground Water yield prospects 50 to 150 m$^3$/hr

5 Semi-consolidated Formations-Tertiary, Mesozoic,Upper Palaeozoic--Siltstone, Claystone, Grit, Sandstone, Shale, Conglomerate, Limestone, including intrusives (Andaman)--Fairly thick but discontinuous aquifers--Limited Ground Water yield prospects below 50m$^3$/hr

6 Consolidated Formations--Sedimentaries, Metasedimentaries, Effusives, Basal crystallines--Mesozoic, Palaeozoic, Precambrian, Archaean--Basalt with Intertrappean Clay, Sandstone, Dolomite, Limestone, Slate, Quartzite, Phyllite, Schist, Gneiss, Marble, Gneissic Complex and associated intrusives (Post-Archaean)--Groundwater restricted to weathered residuum/fracture zones having secondary porosity--Large yield prospects above 20 m$^3$/hr

7 Consolidated Formations--Sedimentaries, Metasedimentaries, Effusives, Basal crystallines--Mesozoic, Palaeozoic, Precambrian, Archaean--Basalt with Intertrappean Clay, Sandstone, Dolomite, Limestone, Slate, Quartzite, Phyllite, Schist, Gneiss, Marble, Gneissic Complex and associated intrusives (Post-Archaen)--Moderate yield prospects 5 to 20 m$^3$/hr

8 Consolidated Formations--Sedimentaries, Meta-sedimentaries, Effusives, Basal crystallines--Mesozoic, Palaeozoic, Precambrian, Archaean--Basalt with Intertrappean Clay, Sandstone, Dolomite, Limestone, Slate, Quartzite, Phyllite, Schist, Gneiss, Marble, Gneissic Complex and associated intrusives (Post-Archaean)--Limited yield prospects below 5 m$^3$/hr

**Fig.1.17.** Geohydrological map of India. (Source: GSI (1969), Central Ground Water Board and other Government organisations.

of availability of copious rainfall. Tropical deciduous forests are distributed in a major part of Peninsular India, mostly in the central and eastern parts and a little in the southern part. These areas have the most important forests of the country. Tropical thorny vegetation is confined to parts of southern and western India, where the rainfall is mostly less than 750 mm. *Acacia* is the most important one associated with thorny shrubs. Subtropical vegetation is restricted to a narrow belt in northwest and eastern Himalaya, between 1000 and 2000 m altitude. Temperate vegetation is exclusively confined to the Himalayan region between altitudes 1500 and 3000 m, where the rainfall varies from 1000 to 2500 mm. Alpine and Sub-alpine vegetation is met with at altitudes from 3000-3600 m in the Himalaya. Littoral and Swamp vegetation is confined to some narrow pockets mainly along the east coast of India. Along some of the coastal margins of deltas occur mangrove, which is an important type of natural vegetation that is to be protected.

## GROUNDWATER

The different physiographic provinces of India and the geological formations therein have quite contrasting capacities to store and permit exploitation of groundwater. For example, Ganga Plains contain good aquifers whereas Deccan Traps have poor aquifers. Figure 1.17 presents the geohydrological map of India, clearly indicating the nature of lithology, stratigraphic horizon/s, nature of the aquifer and possible yield. The map characterises the Indian subcontinent on the basis of unconsolidated, semiconsolidated and consolidated formations with differing ground water yield prospects. However, when dealing with exploration in a specified location, whereas the regional picture may be of some assistance, it is the local condition that must be taken into consideration.

With gradual depletion of this natural resource due to over exploitation and pollution, being caused due to natural (sea water incursion) or anthropogenic causes, it has become imperative to initiate many scientific investigations, using latest technology (geophysical, remote sensing), to find and tap ground water resources in hitherto unknown areas and try to conserve every available source (water-harvesting). Even proper management of estimated resources and methods of rainwater harvesting have become very important.

# 2

# Geology of India: A Synopsis

## INTRODUCTION

> *"A group of distinguished geologists could stand in front of the same outcrop, make the same observations, and come up with different interpretations"- P.J.Wyllie in "The Century before the Millennium: Selected Advances in Petrology", Mem. Geol. Soc. India, No.52, 2003, p.9.*

### Vestiges of the Beginning

Solar System consisting the Sun at its centre and planets, satellites and asteroids surrounding it, forms only a miniscule part of the Universe. The Universe originated over 13 to 15 giga years (Ga) ago with a 'Big Bang'. Solar System grew from a cloud of gas and dust contracting under its own gravitational force into a flattened disc called the Solar Nebula. Condensation of the nebula produced planets and satellites like the Earth, Moon, Mars, Venus, Mercury, Jupiter and Saturn. The early history of the Earth commenced with intense bombardment, impact cratering that triggered melting and volcanism, and degassing of volatiles that led to ocean formation, atmospheric evolution and origin of life. Impact craters and their products are sporadically preserved in the geological record from Archaean to the present. This early phase of the Earth was followed by gravitational differentiation to produce the zoned body of the core, mantle and crust. The formation of the Earth and Solar System is reckoned at 4.56 Ga by Pb-Pb, Sm-Nd and Rb-Sr isotopic dating of lunar rocks and the primitive carbonaceous chondritic meteorites. The vestiges of the early beginnings of the earth are not preserved in the terrestrial rock record and only models based on intelligent speculation exist. These vestiges may be called the 'missing millions' of the Earth's early history.

The record of the oldest events is found in geological provinces that aggregate to hardly 10,000 km$^2$, out of the 150 million km$^2$ of the continental crust. Such rare records are preserved in three large areas, viz., Itsaq Gneiss Complex in the Nuuk region of Greenland, Uivak Gneiss Complex of the adjacent Labrador in Canada, and the Narryer Gneiss Complex of Western Australia. The earliest discovery was in the Itsaq Gneiss Complex (3000 sq. km) where the renowned field geologist, the late V.R. Macgregor, and the outstanding geochronologist S. Moorbath and his colleagues from the Oxford Isotope Geology Laboratory established the presence of the oldest rocks of the earth. The age of the oldest rock was confirmed through robust dating by multichronometric methods at ~ 3.8 Ga. There are other smaller areas from where such ancient rocks are reported, viz., Acasta Gneiss in the Northwest Territories of Canada, Mount Sones and nearby nunataks in Antarctica, and elsewhere in Greenland, China etc. In areas like the Narryer Gneiss of Australia, Beijing in China and Beartooth Mountains in Wyoming, USA, detrital zircons from ancient sediments are dated up to 4200 Ma, but their host rocks are not located. In addition to the rarity of such old rocks, their occurrence in intensely deformed and highly metamorphosed (up to granulite facies) terrains causes serious problems in the identification of their protoliths. Search for such rare remnants in the vast gneiss complexes of Precambrian terrains is like looking for a needle in the haystack, and this calls for mammoth efforts involving enormous volume of isotopic dating at huge cost (Nutman et al 2001). Nonetheless, the quest for the oldest rocks continues worldwide as a thrust area of intensive studies. Rocks of such antiquity are not yet identified in India, and the oldest rocks of 3.5-3.6 Ga are the gneisses of Bastar craton. Vestiges of such events are found in the single crystal SHRIMP zircon U-Pb ages of 3.6 Ga from Dharwar and Singhbhum cratons. Most other cratons and mobile belts of India record rare old events of 3.3-3.5 Ga.

### Geological Time Scale

Geological Time Scale is essentially a global chronostratigraphic (time-rock) scale (Salvador, 1994) that is refined in recent years through global standardization of GSSP (Global Stratotype Section and Point) popularly known as ‘golden spike’. GSSPs are locations where a good example of a global geological event is preserved, and such locations are approved by the ICS (International Commission of Stratigraphy), which is an arm of IUGS (International Union of Geological Sciences). Once the location is ratified by the IUGS, it is accepted as a global boundary (i.e., golden spike) for a particular span of geological time. The first GSSP was identified in the Czech Republic in 1972, and now over 50 golden spikes are identified for the Phanerozoic. The Precambrian has largely remained without GSSP since the rocks are mostly unfossiliferous, and wherever primitive fossils are found, they are not index fossils suitable for stratigraphic correlation. The Precambrian time scale has therefore remained largely chronometric (time unit) without reference to any rock unit that forms the golden spike. The chronometric scale is based on GSSA (Global Standard Stratigraphic Age) that is accepted by consensus, based on the isotopic ages of global Precambrian events. The absolute time boundary is a matter of serious debate, as global Precambrian events are diachronous. Despite advancements in high-precision dating, there are still problems of inter-laboratory variations, reference standards and decay constants. Another serious deficiency is the differing geological interpretation of the same dataset. This is largely overcome by resorting to multiple methods of isotopic dating of suitable rocks from geologically well-studied sections. Notwithstanding these inherent difficulties, the ICS (2004) has constructed International Stratigraphic Chart (ISC) based on Geological Time Scale by Gradstein et al. (2005) that incorporates the results of multiple isotopic dating techniques through debate by a large number of specialists. ISC 2004 is reproduced in the Fig.2.1.

## Precambrian Time Scale

Precambrian encompasses 88% of Earth's history, but the fragmentary nature of its rock record makes it less understood than Phanerozoic. The period from the origin of the earth (~4600 Ma) to the beginning of the terrestrial rock record (~4000 Ma) defined in ICS (2009) as Hadean, named after the Greek mythological underworld Hades (known as Patala Loka in Hindu mythology). This name was coined by Preston Cloud and is now widely adopted by Precambrian geologists. This period is also called Priscoan. The period succeeding Hadean (informal) to the base of Cambrian at 542 Ma is divided into Archaean and Proterozoic Eons, with the dividing line at 2500 Ma by the International Sub-Commission on Precambrian Stratigraphy. The dividing line is 'selected so as to enclose or delimit principal cycles of sedimentation, orogeny and magmatism, but in which boundaries are defined in years without specific reference to any bodies of rock. For practical and scientific reasons, this has been achieved by placing boundaries selectively at times of minimal activity or gaps in the known geological record' (Plumb and James, 1986). This is essentially a chronometric scale as against the chronostratigraphic scale devised for the Phanerozoic.

The Archaean Eon spanning ~1500 million years is divided into four eras, namely, Eoarchaean (from 4000 to 3600 Ma), Palaeoarchaean (3600 to 3200 Ma), Mesoarchaean (3200 to 2800 Ma) and Neoarchaean (2800 to 2500 Ma). Archaean Eon is characterized by the formation of sialic proto-continents that are broadly similar to those of the present day Earth. The cratons are marked by low-grade granite-greenstone terrains as in Africa, Australia, Canada, South America, Europe and India. There are also some high-grade cratonic terrains like the North Atlantic craton. Detrital and chemical sediments are present, besides evidence of biogenic carbon (chemical 'fossils') and emergence of unicellular cyanobacteria. The end of Archaean is marked by an unprecedented vigorous production of continental crust.

The Proterozoic covering a span of about 1950 million years is divided into three eras viz., Palaeoproterozoic (2500 to 1600 Ma), Mesoproterozoic (1600 to 1000 Ma) and Neoproterozoic (1000 to 542 Ma). Unlike the Archaean, Proterozoic is divided into 'Periods' suggesting important geological events, rather than with reference to geographical locations, which has been the norm for Phanerozoic. Palaeoproterozoic is divided into four units at the boundaries of 2300 Ma (Siderian), 2050 (Rhyacian), 1800 Ma (Orosirian) and 1600 Ma (Statherian). Mesoproterozoic is divided into three units viz., at 1400 Ma (Calymmian), 1200 Ma (Ectasian) and 1000 Ma (Stanian). Neoproterozoic is divided into three units at 850 Ma (Tonian), 630 Ma (Cryogenian) and 542 Ma (Ediacaran). These divisions of Proterozoic into eras have gained wide acceptance, but the periods have not yet become popular. Proterozoic is a period of great crustal stabilization marked by continental rifts, intracratonic basins, mafic dyke swarms, continental flood basalts and Pb-Zn mineralisation, along with widespread and voluminous stable shelf or platformal successions of quartzite-carbonate-pelite (QCP) suite, evaporites and phosphorites.

Monumental changes took place in the global environment at the Precambrian-Cambrian boundary. "The significant event during the 'Cambrian biological explosion' (Marshall, 2006) was the rapid development of forms with exoskeletons and biomineralisation, but some soft-bodied Ediacaran faunas did survive," (Narbonne, 2005; McCall, 2006) because they are incredibly preserved in suitable rocks in several parts of the world. "Precambrian-Cambrian boundary was the end of a beginning and the beginning of the end" (Windley, 1995, p.240-243). A typical example of life in the Precambrian of India is illustrated in Plate 2.1.

### Phanerozoic Time Scale

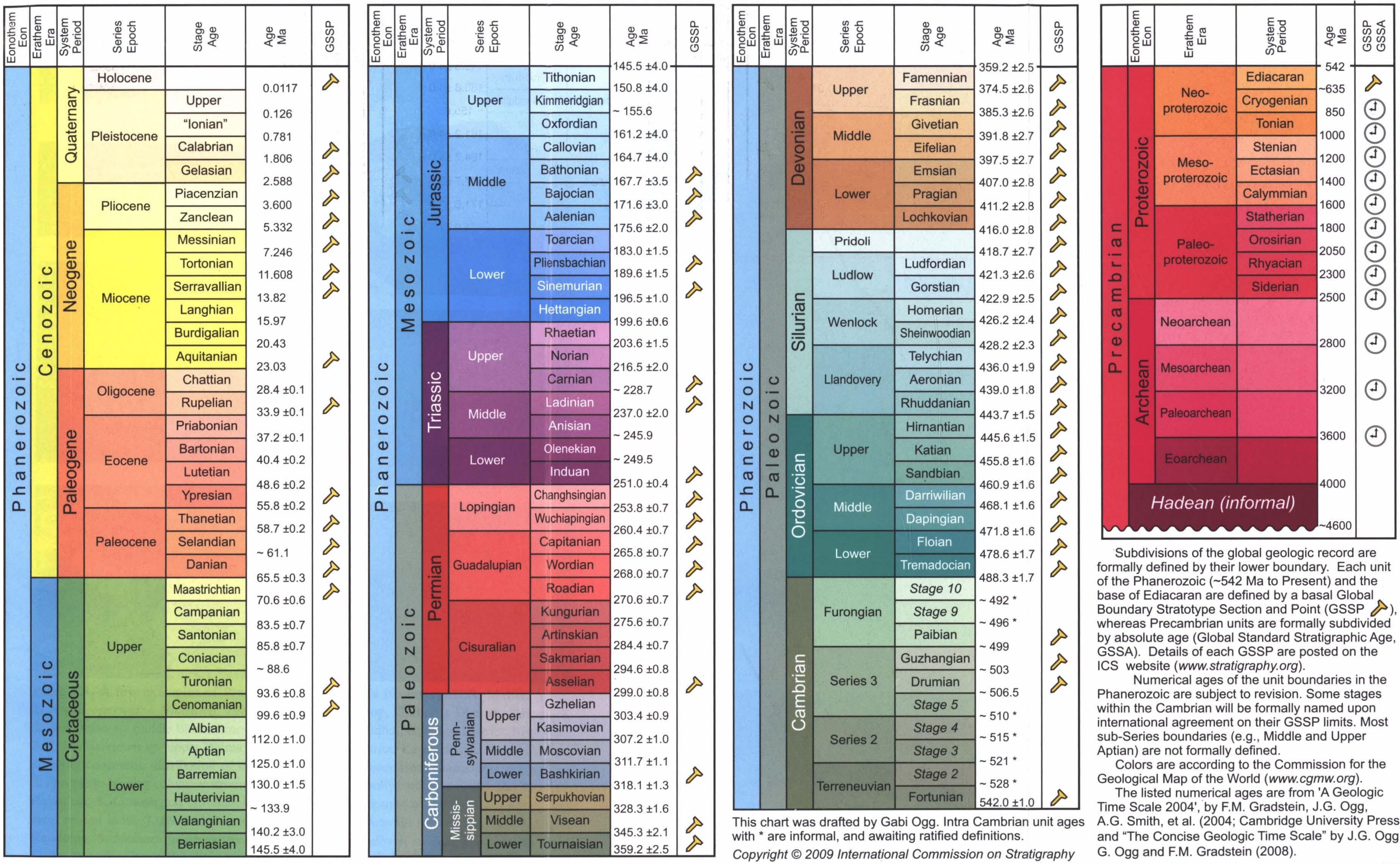
The Phanerozoic extending over a period of 542 m.y. has been divided into Palaeozoic (291 m.y.), Mesozoic (86 m.y.) and Cenozoic (65 m.y.) eras. Whereas there are records of marine strata and life during this long span of time in the extra-peninsular India, if not continuously in any single region, the same cannot be said of strata and life in the peninsular India. Though in the uppermost horizons of the Proterozoic strata, in certain parts of the peninsula, Cambrian biota are believed to occur, unequivocal evidences have not yet been found. It is not unlikely that in the near future they may come to light. The geological record clearly indicates that it is interspersed by catastrophic events. About four major periods of mass extinction have been

ICS

# INTERNATIONAL STRATIGRAPHIC CHART

IUGS

International Commission on Stratigraphy



| Eonothem Eon | Erathem Era | System Period | Series Epoch | Stage Age | Age Ma | GSSP |
|---|---|---|---|---|---|---|
| Phanerozoic | Cenozoic | Quaternary | Holocene | | 0.0117 | ⚑ |
| | | | Pleistocene | Upper | 0.126 | |
| | | | | "Ionian" | 0.781 | |
| | | | | Calabrian | 1.806 | ⚑ |
| | | | | Gelasian | 2.588 | ⚑ |
| | | Neogene | Pliocene | Piacenzian | 3.600 | ⚑ |
| | | | | Zanclean | 5.332 | ⚑ |
| | | | Miocene | Messinian | 7.246 | ⚑ |
| | | | | Tortonian | 11.608 | ⚑ |
| | | | | Serravallian | 13.82 | ⚑ |
| | | | | Langhian | 15.97 | |
| | | | | Burdigalian | 20.43 | |
| | | | | Aquitanian | 23.03 | ⚑ |
| | | Paleogene | Oligocene | Chattian | 28.4 ±0.1 | |
| | | | | Rupelian | 33.9 ±0.1 | ⚑ |
| | | | Eocene | Priabonian | 37.2 ±0.1 | |
| | | | | Bartonian | 40.4 ±0.2 | |
| | | | | Lutetian | 48.6 ±0.2 | |
| | | | | Ypresian | 55.8 ±0.2 | ⚑ |
| | | | Paleocene | Thanetian | 58.7 ±0.2 | ⚑ |
| | | | | Selandian | ~ 61.1 | ⚑ |
| | | | | Danian | 65.5 ±0.3 | ⚑ |
| | Mesozoic | Cretaceous | Upper | Maastrichtian | 70.6 ±0.6 | ⚑ |
| | | | | Campanian | 83.5 ±0.7 | |
| | | | | Santonian | 85.8 ±0.7 | |
| | | | | Coniacian | ~ 88.6 | |
| | | | | Turonian | 93.6 ±0.8 | ⚑ |
| | | | | Cenomanian | 99.6 ±0.9 | ⚑ |
| | | | Lower | Albian | 112.0 ±1.0 | |
| | | | | Aptian | 125.0 ±1.0 | |
| | | | | Barremian | 130.0 ±1.5 | |
| | | | | Hauterivian | ~ 133.9 | |
| | | | | Valanginian | 140.2 ±3.0 | |
| | | | | Berriasian | 145.5 ±4.0 | |

| Eonothem Eon | Erathem Era | System Period | Series Epoch | Stage Age | Age Ma | GSSP |
|---|---|---|---|---|---|---|
| | | | | | 145.5 ±4.0 | |
| Phanerozoic | Mesozoic | Jurassic | Upper | Tithonian | 150.8 ±4.0 | |
| | | | | Kimmeridgian | ~ 155.6 | |
| | | | | Oxfordian | 161.2 ±4.0 | |
| | | | Middle | Callovian | 164.7 ±4.0 | |
| | | | | Bathonian | 167.7 ±3.5 | ⚑ |
| | | | | Bajocian | 171.6 ±3.0 | ⚑ |
| | | | | Aalenian | 175.6 ±2.0 | ⚑ |
| | | | Lower | Toarcian | 183.0 ±1.5 | |
| | | | | Pliensbachian | 189.6 ±1.5 | ⚑ |
| | | | | Sinemurian | 196.5 ±1.0 | ⚑ |
| | | | | Hettangian | 199.6 ±0.6 | |
| | | Triassic | Upper | Rhaetian | 203.6 ±1.5 | |
| | | | | Norian | 216.5 ±2.0 | |
| | | | | Carnian | ~ 228.7 | ⚑ |
| | | | Middle | Ladinian | 237.0 ±2.0 | ⚑ |
| | | | | Anisian | ~ 245.9 | |
| | | | Lower | Olenekian | ~ 249.5 | |
| | | | | Induan | 251.0 ±0.4 | ⚑ |
| | Paleozoic | Permian | Lopingian | Changhsingian | 253.8 ±0.7 | ⚑ |
| | | | | Wuchiapingian | 260.4 ±0.7 | ⚑ |
| | | | Guadalupian | Capitanian | 265.8 ±0.7 | ⚑ |
| | | | | Wordian | 268.0 ±0.7 | ⚑ |
| | | | | Roadian | 270.6 ±0.7 | ⚑ |
| | | | Cisuralian | Kungurian | 275.6 ±0.7 | |
| | | | | Artinskian | 284.4 ±0.7 | |
| | | | | Sakmarian | 294.6 ±0.8 | |
| | | | | Asselian | 299.0 ±0.8 | ⚑ |
| | | Carboniferous<br>Pennsylvanian | Upper | Gzhelian | 303.4 ±0.9 | |
| | | | | Kasimovian | 307.2 ±1.0 | |
| | | | Middle | Moscovian | 311.7 ±1.1 | |
| | | | Lower | Bashkirian | 318.1 ±1.3 | ⚑ |
| | | Carboniferous<br>Mississippian | Upper | Serpukhovian | 328.3 ±1.6 | |
| | | | Middle | Visean | 345.3 ±2.1 | ⚑ |
| | | | Lower | Tournaisian | 359.2 ±2.5 | ⚑ |

| Eonothem Eon | Erathem Era | System Period | Series Epoch | Stage Age | Age Ma | GSSP |
|---|---|---|---|---|---|---|
| | | | | | 359.2 ±2.5 | |
| Phanerozoic | Paleozoic | Devonian | Upper | Famennian | 374.5 ±2.6 | ⚑ |
| | | | | Frasnian | 385.3 ±2.6 | ⚑ |
| | | | Middle | Givetian | 391.8 ±2.7 | ⚑ |
| | | | | Eifelian | 397.5 ±2.7 | ⚑ |
| | | | Lower | Emsian | 407.0 ±2.8 | ⚑ |
| | | | | Pragian | 411.2 ±2.8 | ⚑ |
| | | | | Lochkovian | 416.0 ±2.8 | ⚑ |
| | | Silurian | Pridoli | | 418.7 ±2.7 | ⚑ |
| | | | Ludlow | Ludfordian | 421.3 ±2.6 | ⚑ |
| | | | | Gorstian | 422.9 ±2.5 | ⚑ |
| | | | Wenlock | Homerian | 426.2 ±2.4 | ⚑ |
| | | | | Sheinwoodian | 428.2 ±2.3 | ⚑ |
| | | | Llandovery | Telychian | 436.0 ±1.9 | ⚑ |
| | | | | Aeronian | 439.0 ±1.8 | ⚑ |
| | | | | Rhuddanian | 443.7 ±1.5 | ⚑ |
| | | Ordovician | Upper | Hirnantian | 445.6 ±1.5 | ⚑ |
| | | | | Katian | 455.8 ±1.6 | ⚑ |
| | | | | Sandbian | 460.9 ±1.6 | ⚑ |
| | | | Middle | Darriwilian | 468.1 ±1.6 | ⚑ |
| | | | | Dapingian | 471.8 ±1.6 | ⚑ |
| | | | Lower | Floian | 478.6 ±1.7 | ⚑ |
| | | | | Tremadocian | 488.3 ±1.7 | ⚑ |
| | | Cambrian | Furongian | *Stage 10* | ~ 492 * | |
| | | | | *Stage 9* | ~ 496 * | |
| | | | | Paibian | ~ 499 | ⚑ |
| | | | Series 3 | Guzhangian | ~ 503 | ⚑ |
| | | | | Drumian | ~ 506.5 | ⚑ |
| | | | | *Stage 5* | ~ 510 * | |
| | | | Series 2 | *Stage 4* | ~ 515 * | |
| | | | | *Stage 3* | ~ 521 * | |
| | | | Terreneuvian | *Stage 2* | ~ 528 * | |
| | | | | Fortunian | 542.0 ±1.0 | ⚑ |

| Eonothem Eon | Erathem Era | System Period | Age Ma | GSSP GSSA |
|---|---|---|---|---|
| | | | 542 | |
| Precambrian<br>Proterozoic | Neo-proterozoic | Ediacaran | ~635 | ⚑ |
| | | Cryogenian | 850 | ◷ |
| | | Tonian | 1000 | ◷ |
| | Meso-proterozoic | Stenian | 1200 | ◷ |
| | | Ectasian | 1400 | ◷ |
| | | Calymmian | 1600 | ◷ |
| | Paleo-proterozoic | Statherian | 1800 | ◷ |
| | | Orosirian | 2050 | ◷ |
| | | Rhyacian | 2300 | ◷ |
| | | Siderian | 2500 | ◷ |
| Precambrian<br>Archean | Neoarchean | | 2800 | ◷ |
| | Mesoarchean | | 3200 | ◷ |
| | Paleoarchean | | 3600 | ◷ |
| | Eoarchean | | 4000 | |
| | *Hadean (informal)* | | ~4600 | |

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic (~542 Ma to Present) and the base of Ediacaran are defined by a basal Global Boundary Stratotype Section and Point (GSSP ⚑), whereas Precambrian units are formally subdivided by absolute age (Global Standard Stratigraphic Age, GSSA). Details of each GSSP are posted on the ICS website (*www.stratigraphy.org*).

Numerical ages of the unit boundaries in the Phanerozoic are subject to revision. Some stages within the Cambrian will be formally named upon international agreement on their GSSP limits. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Colors are according to the Commission for the Geological Map of the World (*www.cgmw.org*).

The listed numerical ages are from 'A Geologic Time Scale 2004', by F.M. Gradstein, J.G. Ogg, A.G. Smith, et al. (2004; Cambridge University Press) and "The Concise Geologic Time Scale" by J.G. Ogg, G. Ogg and F.M. Gradstein (2008).

This chart was drafted by Gabi Ogg. Intra Cambrian unit ages with * are informal, and awaiting ratified definitions.

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August 2009

**Fig.2.1.** International Stratigraphic Chart by International Commission on Stratigraphy (ICS, 2009).

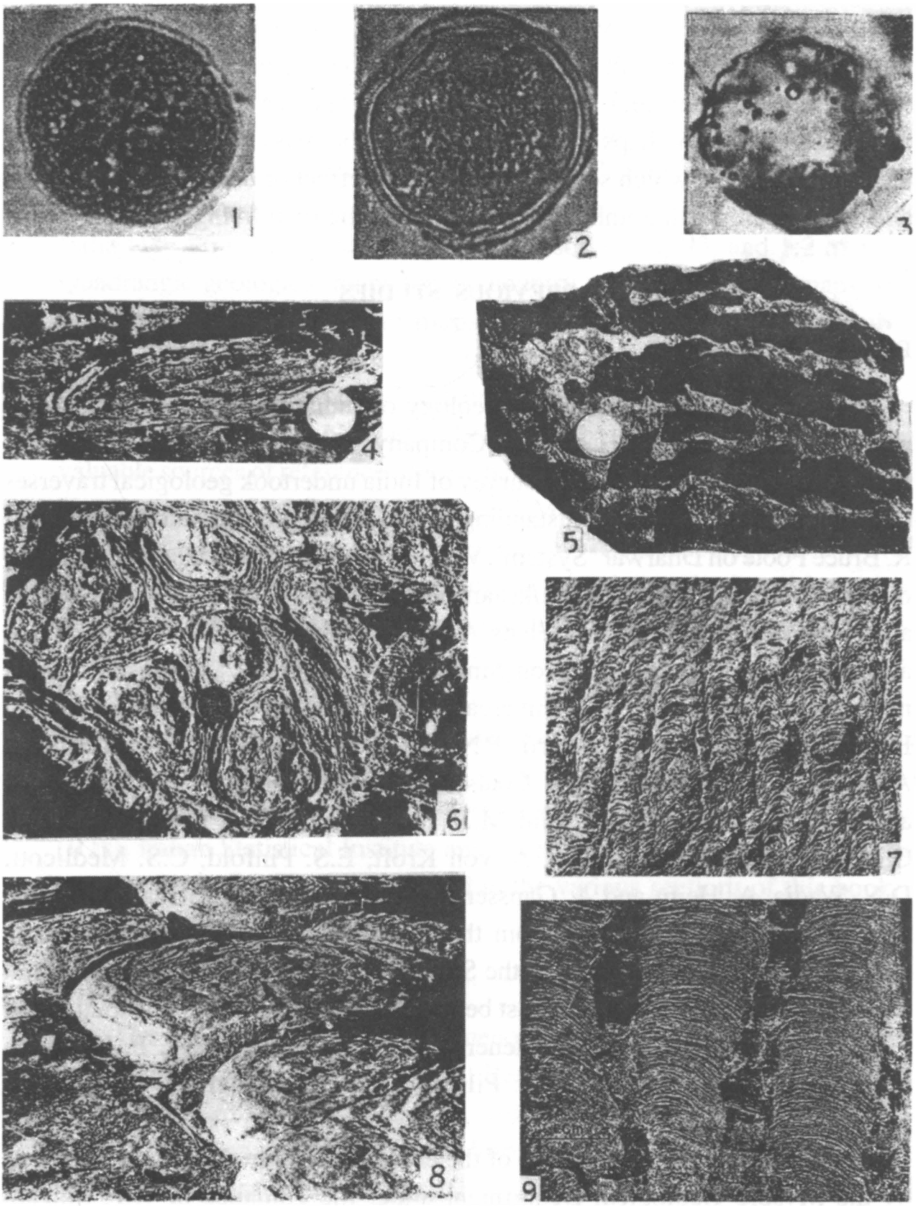


**Plate 2.1.** A few examples of Precambrian life in India (Courtesy: U.B. Mallikarjuna). **1.** *Archaeopertusina Naumova*, 1960; lower Bhima Group, Gulbarga District, Karnataka. **2.** *Tasmanites* sp. middle Bhima limestone of Honali and Mudhol, Gulbarga District, Karnataka. **3.** *Leiosphaeridum* sp. upper Bhima Group, Gulbarga District, Karnataka. **4.** *Colonella* msp. showing concentric distribution of laminae from the Dodguni area (Chitradurga schist belt). **5.** Phosphate-bearing columnar stromatolite enclosed in a wholly carbonate matrix near Udaipur, Rajasthan. **6.** Conophyton (stromatolites) in the Lohar Dolomite of the Bijawar Group, Joga area, central India. **7.** *Masloviella columnaris* in Kanpur (Aravalli stromatolite) near Udaipur, Rajasthan. **8.** *Maiharia maiharensis* (Acaceilla) upper Vindhyan stromatolite from the Sirbu Shale, Bhander Group (locality: Maihar, Satna). **9.** *Kussiella kussiensis* Komar from Jammu Limestone (lower Riphean), Lesser Himalaya.

recognized around 439 Ma (Lower Silurian), 364 Ma (Upper Devonian), 250 Ma (Upper Permian), and 65 Ma (Cretaceous/Tertiary – K/T boundary), when almost 95 per cent of plant and animal species appear to have been exterminated. It is perhaps possible to connect the mass extinction with extra-terrestrial impacts, which seem to have had the effect of destroying everything and making the earth uninhabitable to most of the then living species.

## PREVIOUS STUDIES

### Pioneers in Geology

The earliest references to the geology of India are found in the traverse notes of the Officers of East India Company who were amateur geologists. Later, officers of the Geological Survey of India undertook geological traverses in different parts of India. Outstanding works of the pioneers include those of R. Bruce Foote on Dharwar 'System', W. King on Cuddapah Basin, T.H. Holland on Charnockite 'Series', H. Crookshank and P.K. Ghosh on Bastar, T.L. Walker and H. Crookshank on Eastern Ghats, A.M. Heron and B.C. Gupta on Rajasthan and J.A. Dunn and A.K. Dey on Singhbhum. In central and western India, many officers worked in different areas viz., V. Ball, C.A. Hacket, T. Oldham, H.B. Medlicott, W.T. Blanford, P.N. Bose, F.R. Mallet, E. Vredenburg, A.B. Wynne, H.F. Blanford, A.M. Coulson, C.S. Middlemiss, C.S. Fox, J.B. Auden and W.D. West. H.C. Jones and M.S. Krishnan worked in eastern India. C.L. Griesbach, H.H. Hayden, A. von Kroft, E.S. Pinfold, C.S. Medlicott, D.N. Wadia, A. Heim and A. Gansser investigated sections of the Himalaya. Simultaneously, almost right from the inception of the Survey, the fossils collected either by the officers of the Survey or by others were studied both in India and abroad, and mention must be made of the significant contributions of F.R.C. Reed, F. Stoliczka, C. Diener, L.F. Spath, F. Noetling, F. Kossmat, R. Lydekkar, C.A. Matley, G.E. Pilgrim, G de P. Cotter, O. Feismantel, A.C. Seward and Birbal Sahni.

An excellent geological map of the erstwhile Mysore State was produced by the Mysore Geological Department under the guidance of W.F. Smeeth and P. Sampat Iyengar in 1915. Revision mapping in some areas was carried out by S. Jayaram, B. Rama Rao, C.S. Pichamuthu and a few others. The Hyderabad and Travancore Geological Surveys also produced fundamental geological data and maps. Prof. C. Mahadevan and P.T. Chacko also made important contributions. The results of early studies were published in four volumes as the Manual of Geology of India and Burma (First Edition) in 1879, 1881 &1887 by H.B. Medlicott, W.T. Blanford, V. Ball and F.R. Mallet. The Second Edition by R.D. Oldham was published in 1893 (Reprinted in 1994). L.L. Fermor published his monumental memoir in 1936 on the Correlation of

Ancient Schistose Rocks of Peninsular India. The Third Edition of the Manual of Geology of India and Burma was produced in four volumes by E.H. Pascoe (1950, 1959, 1964, 1976) and this continues until today as an authentic manual. The Fourth Edition of the Manual is being published (GSI, 2004, 2006). Geology of States of India (GSI Misc. Publ. 30) provides synoptic accounts. Geological maps were also periodically produced by the Geological Survey of India (1"= 96 miles scale in 1964, 1:5 M scale in 1993, and 1:2 M in 1998). Quadrangle geological maps for the country, 1:1 million scale maps for most States and 1:500,000 scale maps for some States have been published periodically. Thematic maps on tectonics, metamorphism, geomorphology and isotopic age were also published from time to time. Classical textbooks on the geology of India by D.N. Wadia (1975), and by M.S. Krishnan (1982) are still valuable sources of reference. Recent publications on the subject are by Ravindra Kumar (1996), S.M. Naqvi (2005) and M.N. Balasubrahmanyan (2006). An outline of the geology of Indian Subcontinent is provided by A.B. Roy (2005).

The pioneering efforts at geological mapping and mineral investigations are succeeded by outstanding contributions from various organisations like the Geological Survey of India, Atomic Minerals Directorate for Exploration and Research, Oil and Natural Gas Commission (now Corporation), National Geophysical Research Institute, Wadia Institute of Himalayan Geology, Centre for Earth Science Studies, Birbal Sahni Institute of Palaeobotany, Physical Research Laboratory, IICTs (formerly RRLs), Indian Institute of Technology (IITs), Indian Statistical Institute and several Universities in India. The salient results of these studies are included in the various sections of this book.

### Geophysical Studies

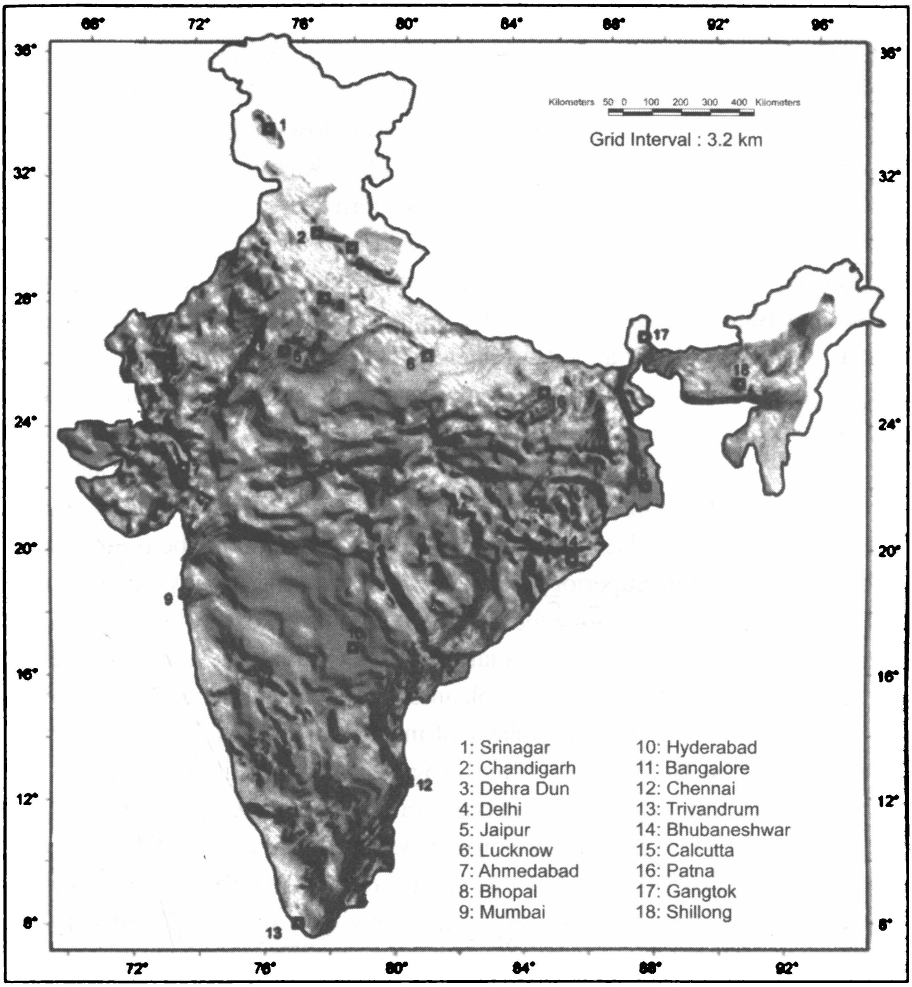
Gravity studies in India commenced as early as in 1865, and after early compilations, National Geophysical Research Institute published gravity map series (NGRI, 1978) on 1:5M scale with a contour interval of 10 mGal, along with an explanatory brochure. Subsequent data were synthesized by Verma (1991) and Balakrishnan (1997). The NGRI maps were digitized using "Auto Trace and Digitize" methodology to produce colour image maps and shaded relief maps (Fig.2.2) by Sreedhar Murthy (1999). The maps show that negative anomalies characterize the Indian shield, with high values of –380 mGal over the Himalaya. Gravity lows are seen over the gneisses, Deccan Trap, 'Purana' Basins (except Cuddapah), Godavari and Mahanadi graben, Indo-Gangetic alluvium and coastal sediments. Gravity highs are seen in the charnockite massifs of south India, part of Cuddapah basin, Western Ghats and Shillong Plateau. Gravity highs over Saurashtra, Kachchh, Thar Desert and eastern Singhbhum appear to be anomalous. Bouguer anomalies also bring out regional structural trends that are enhanced by shaded relief maps. Free air anomaly maps reflect the topography and its geological control. Isostatic anomaly maps show vertical movements and regional isostatic compensation. A conspicuous gravity feature is the overcompensation in south India due to the large gravity low ('geoid') in the Indian Ocean. Aeromagnetic anomaly map of India (Fig.2.3) produced by the AMSE Wing of the Geological Survey of India (Mathew et al. 2001), based on high altitude airborne magnetometric surveys, brings out major tectonic elements, with magnetic highs over charnockite massifs and iron ore belts, and magnetic lows over the rest of the terrain (Harikumar et al.2000; Rajaram et al. 2006). Specific regions covered by low-altitude surveys have brought out clearly the mafic supracrustal belts, dykes and lineaments (Project VASUNDHARA, 1994). Reflection and refraction seismology, broad-band teleseismic surveys, magneto-telluric and electrical resistivity surveys, and heat flow and palaeomagnetic studies in India are confined to specific regions for specific purposes, and are described in appropriate sections in this book. The status of geophysical studies in India is summarised in the following volumes: Qureshy and Hinze (1989), GSI (1994, 2002) Mahadevan (1994), Reddi et al. (1995), Radhakrishna and Piper (1999), Mahadevan et al. (2003) and papers by Murthy (2007), Bijendra Singh and Dimri (2008).

### Geochemical and Geochronological Studies

Geochemical studies, including the state-of-the-art high quality instrumental data, are available for specific geological units, and these are described in appropriate sections. An overview of important geochemical studies is given in Naqvi (2005). Electron microprobe studies of mineral assemblages and their critical textures have been carried out mainly from high-grade terrains for generating P-T-t paths for interpretation of metamorphic and tectonic evolution. Geochronological studies commenced early in India, with K-Ar data produced on a variety of rocks. Presently, Rb-Sr isochrons are available for most cratons and mobile belts, but these reflect only the younger events in a polychronic terrain. A variety of U-Pb dates is now being generated widely all over the world to overcome this limitation. Such data are available for limited regions in India mainly through international collaboration. These data are also dealt with in appropriate sections of the text.

## TECTONIC FRAMEWORK OF INDIA

Precambrian shields all over the world like those of Canada, Africa, Australia, South America, Russia, China and India are divided into structural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1: Srinagar
2: Chandigarh
3: Dehra Dun
4: Delhi
5: Jaipur
6: Lucknow
7: Ahmedabad
8: Bhopal
9: Mumbai
10: Hyderabad
11: Bangalore
12: Chennai
13: Trivandrum
14: Bhubaneshwar
15: Calcutta
16: Patna
17: Gangtok
18: Shillong

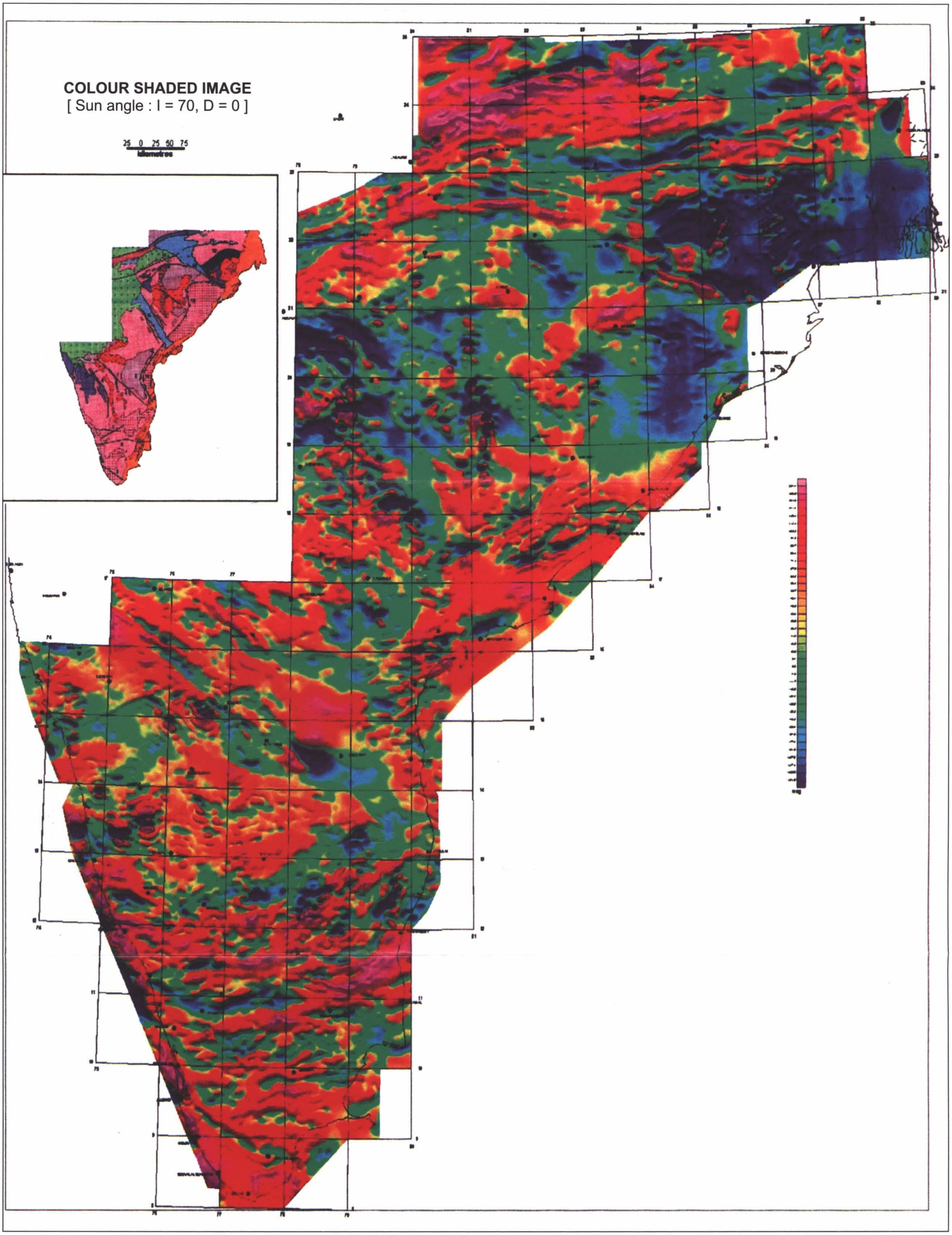
**Fig.2.2.** Bouguer gravity anomaly colour image of India (after Sreedhar Murthy, 1999).

provinces (Superior, Churchill etc. in Canada) or tectonic blocks (Yilgarn, Pilbara etc. in Western Australia). The African shield is traditionally divided into cratons and mobile belts. This division into cratons and mobile belts is now widely adopted in Precambrian literature in general, and in Canada and Australia in particular. This terminology has a genetic flavour as distinct from sterile terms like provinces and blocks. Despite semantic debate on their applicability, the broad contours of these definitions are widely understood, and therefore the classification into cratons and mobile belts is followed in this book. Mobile belts refer to trans-cratonic orogenic belts as against the intra-cratonic fold belts etc. that are described here as orogens.

The Indian shield is a mosaic of cratons and mobile belts (Fig 2.4). *Cratons* are broad central areas of continents that have remained tectonically stable for prolonged periods. They are affected only by younger epeirogenic movements. They are isostatically positive areas dominated by Precambrian 'crystalline rocks' that are overlain by younger cover rocks. Ancient cratons are distinguished by granite-greenstone terrains or low-grade terrains, such as Superior and Slave in Canada, Wyoming in USA, Kaapvaal and Zimbabwe in Southern Africa, Yilgarn and Pilbara in Western Australia, Sao Francisco in South America, Karelia in Russia and Finland, and the North China craton. In contrast to the normally low-grade cratons, some cratons like the North Atlantic, Aldan and Baltic are characterized by high-grade terrains or gneiss-granulite terrains (*see* Passchier et al. 1990). Such high-grade cratons possibly represent deeper crustal levels, as compared to the shallower low-grade terrains. *Mobile belts* are curvilinear, high-grade, gneiss-granulite belts that surround the cratons. They are separated from the cratons by crustal scale ductile shear zones. The best examples of mobile belts are the Limpopo and Mozambique in Africa, Grenville in Canada and Eastern Ghats of India. Some mobile belts are of low-grade, like the Circum-Superior mobile belt of Canada and Albany-Fraser mobile belt of Australia. The mobile belts are mostly Proterozoic in age, and are characterized by lithological association of QCP (quartzite-carbonate-pelite) suite, with or without noticeable volcanics. There are also orogens or fold-thrust belts that occur at the periphery of individual cratons, but are not trans-cratonic, like the North Proterozoic orogen around Singhbhum craton and Aravalli-Delhi orogen around Aravalli craton. There are also intra-cratonic orogens like the Kotri-Dongargarh orogen within Bastar craton. All these types of belts are also called loosely in literature as mobile belts, but such broad-based definitions tend to make the terminology very diffuse. These belts are called *orogens* in this book for want of better terminology.

## Tectonic Divisions of Indian Shield

*Previous Work*: Fermor (1936) provided the first comprehensive division of the Indian shield into charnockitic and non-charnockitic regions. The regions were sub-divided into several provinces of different types. Regional structural trendlines (Fig 2.5) marking major fold axes were later used to divide the shield into areas of Dharwar strike, Eastern Ghats strike, Satpura strike, Mahanadi strike etc (Krishnan, 1961). Since the trendlines are cumulative products of superposed deformation related to different orogenic events, the use of regional strike as a valid basis for tectonic division was questioned (Naha, 1964). Another division was by orogenic events defined by isotopic dating (Holmes, 1955). The concept of various protocontinents forming the Indian shield was adopted by Pichamuthu (1970) and Naqvi et al. (1974), following Engel (1963) for North America. Rogers (1986) proposed that the Indian shield comprised five


COLOUR SHADED IMAGE
[ Sun angle : I = 70, D = 0 ]
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kilometres

**Fig 2.3.** IRGF corrected aeromagnetic map of India by Geological Survey of India, 2001.

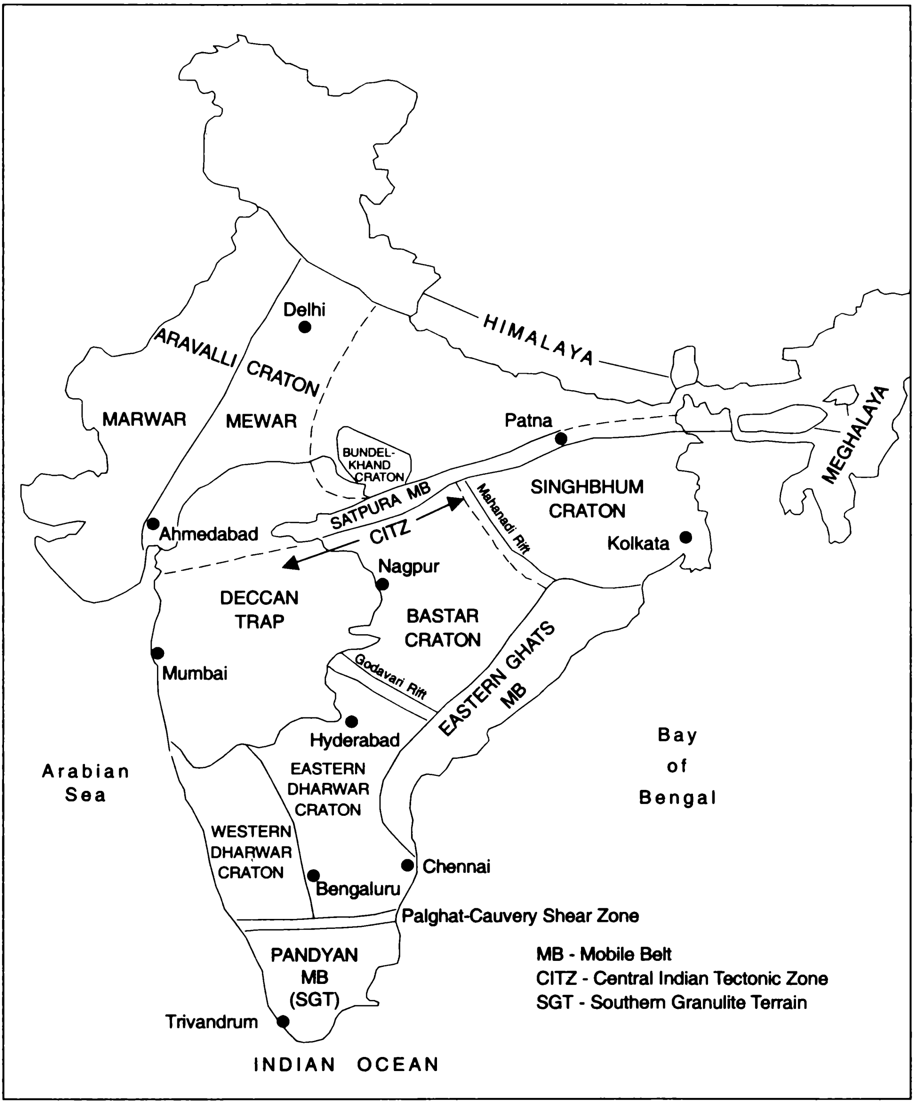

HIMALAYA
MEGHALAYA
ARAVALLI CRATON
MARWAR
MEWAR
Delhi
BUNDEL-KHAND CRATON
Patna
SATPURA MB
CITZ
Mahanadi Rift
SINGHBHUM CRATON
Kolkata
Ahmedabad
Nagpur
DECCAN TRAP
BASTAR CRATON
Mumbai
Godavari Rift
EASTERN GHATS MB
Hyderabad
Arabian Sea
EASTERN DHARWAR CRATON
Bay of Bengal
WESTERN DHARWAR CRATON
Chennai
Bengaluru
Palghat-Cauvery Shear Zone
PANDYAN MB (SGT)
Trivandrum
INDIAN OCEAN
MB - Mobile Belt
CITZ - Central Indian Tectonic Zone
SGT - Southern Granulite Terrain

**Fig.2.4.** Tectonic Divisions of the Indian Shield.

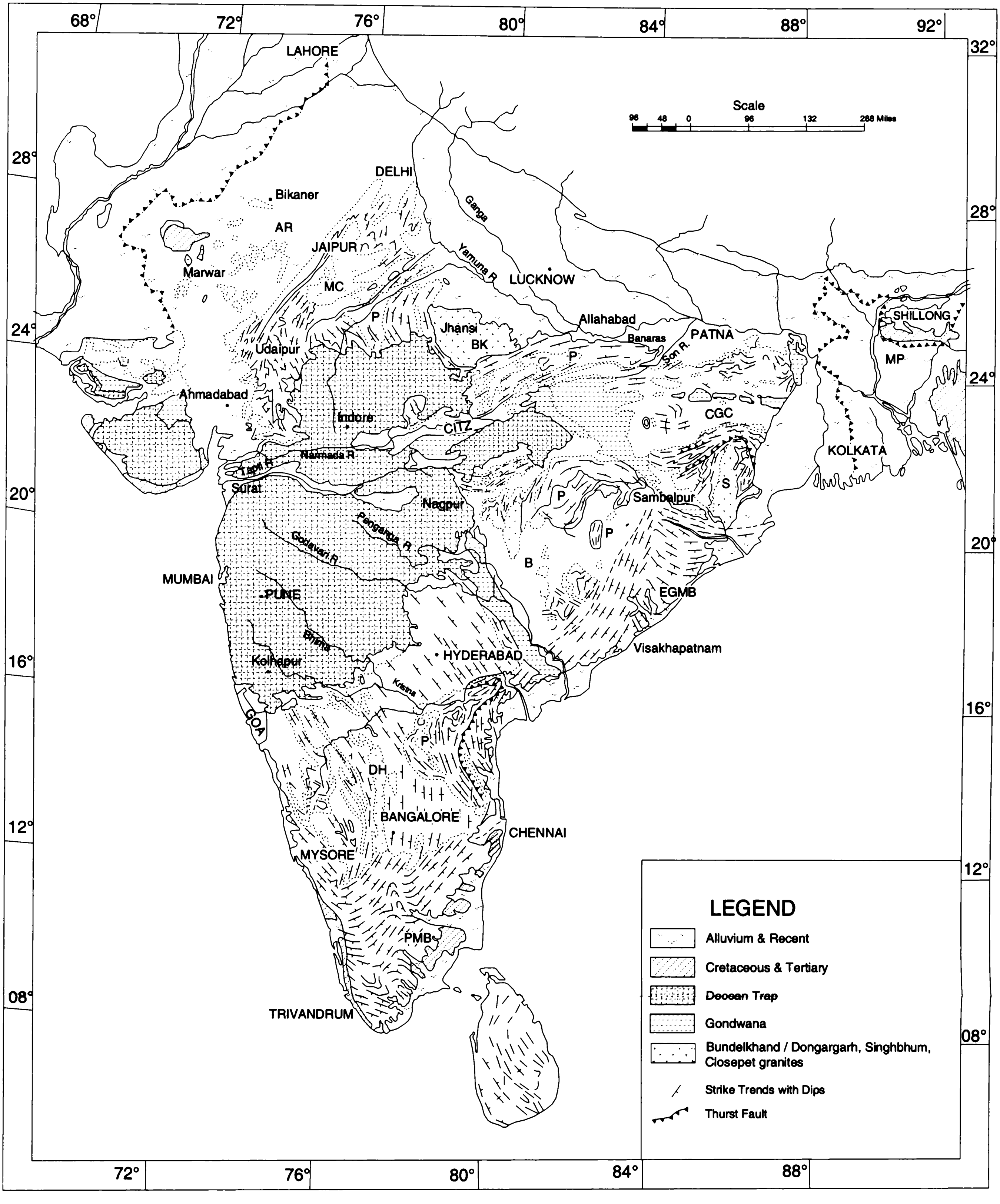
provinces (Dharwar along with granulite terrain, Bhandara, Singhbhum, Aravalli and Eastern Ghats), which were separated by four major joins. Naqvi and Rogers (1987) adopted the view of Swami Nath et al. (1976) of dividing the Dharwar craton into two blocks viz., Eastern and Western Dharwar cratons. Radhakrishna and Naqvi (1986) identified three Precambrian nuclei (Karnataka, Jeypore-Bastar and Singhbhum) separated by two major zones of reworking (mobile belts). Later, Radhakrishna and Ramakrishnan (1988) divided the shield into two blocks, viz., Southern and Northern, separated by Son-Narmada Lineament, each block consisting of welded cratonic nuclei. These authors also reiterated the importance of Palghat-Cauvery (Palakkad-Kaveri) shear zone in separating the two blocks of southern India, following Vemban et al. (1977) and Drury et al. (1984). This scheme is followed in the book.

The 'terrane' concept (*see* Howell, 1989), based on the identification of Cordilleran Suspect Terranes, is now being increasingly applied to Precambrian regions of the world. Accordingly, Radhakrishna (1989) divided the Precambrian of India into many tectono-stratigraphic terranes. It is still a moot question whether each craton or mobile belt is a terrane by itself or consists of many smaller terranes (Rogers and Mauldin, 1994). The latter approach is gaining currency with the terrane classifications proposed for Eastern Ghats mobile belt, Southern Granulite Terrain and Aravalli craton by various authors, following the initial application of the concept to Greenland in the North Atlantic craton (Friend et al. 1988).

### Present Tectonic Division

Indian shield (Geological Map in the pouch) consists of five major Archaean cratons viz., *Dharwar, Bastar and Singhbhum in the Southern Block, Bundelkhand* and *Aravalli in the Northern Block.* There are three prominent Proterozoic mobile belts, viz. *Eastern Ghats mobile belt* fringing Dharwar, Bastar and Singhbhum cratons, *Pandyan mobile belt* fringing Dharwar craton, and *Satpura mobile belt* linking the Northern and Southern Blocks and extending into Shillong Plateau. The Himalayan orogenic belt bounding the Indian shield to the north is largely a Tertiary mountain belt that has a Proterozoic foundation. The Precambrian of Himalaya is described under the Chapter 4 on mobile belts, and the remaining portions of the Himalaya are covered in the Chapters 6,7,8,10 and 11. Apart from the Precambrian cratons and mobile belts, the younger cover in the Indian shield include the following:

(1) Proterozoic sedimentary basins called in Indian geological terminology as the Purana basins.
(2) The vast flood basalt province at the Cretaceous-Tertiary boundary (K-T boundary) known as Deccan Trap or Deccan Volcanic Province (DVP) in western and central India with its outlier at Rajahmundry in southern India.
(3) Rajmahal and Sylhet Traps in eastern India.
(4) Coal-bearing Gondwana successions in Damodar, Satpura, Mahanadi and Godavari rifts.
(5) Cretaceous marine incursions in Narmada valley, at Tiruchirapalli (Trichinopoly) in the Cauvery delta and in Meghalaya.
(6) Coastal Gondwana, Tertiary and Quaternary sediments with local volcanics.
(7) Holocene (Recent) sediments along major river valleys; Tertiary and Quaternary sediments at the Himalayan foothills and in Indo-Gangetic and Brahmaputra plains (including the Bengal and Indus fans).
(8) Phanerozoic successions in the Himalaya.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DELHI
Bikaner
AR
JAIPUR
Marwar
MC
Ganga
Yamuna R.
LUCKNOW
P
Udaipur
Jhansi
BK
Allahabad
Banaras
Son R.
PATNA
SHILLONG
MP
Ahmadabad
Indore
CITZ
CGC
KOLKATA
Narmada R.
Tapti R.
Surat
Nagpur
Sambalpur
S
Penganga R.
Godavari R.
B
MUMBAI
PUNE
EGMB
Bhima
Visakhapatnam
Kolhapur
HYDERABAD
Krisna
GOA
DH
BANGALORE
CHENNAI
MYSORE
PMB
TRIVANDRUM
LEGEND
Alluvium & Recent
Cretaceous & Tertiary
Deccan Trap
Gondwana
Bundelkhand / Dongargarh, Singhbhum, Closepet granites
Strike Trends with Dips
Thurst Fault

**Fig.2.5.** Structural Trend Line Map of India (after Narayanaswamy, 1966).

## DESCRIPTION OF GEOLOGICAL DIVISIONS

### Cratons

*Dharwar Craton*

Dharwar craton is a classical greenstone-granite terrain that is divided into Western and Eastern Dharwar cratons (WDC and EDC), separated by the Chitradurga Shear Zone close to the linear Closepet Granite. The *WDC*, called Karnataka Nucleus by Radhakrishna and Naqvi (1986), consists mainly of Tonalite-Trondhjhemite-Granodiorite (TTG) gneisses accreted during a major orogeny at 3000 Ma (Peninsular Gneiss), with earlier events recorded at 3300-3400 Ma. Numerous narrow linear belts and enclaves of Sargur Group (3100-3300 Ma) are seen within the TTG gneisses, mainly in the south. The bigger belts of Sargur Group are rich in amphibolites, ultramafic rocks (including spinifex textured komatiites), BIF, and subordinate QCP (quartzite-carbonate-pelite) sediments. Bedded barite and detrital chromite layers in fuchsite quartzite are seen rarely. The sequence is intruded by layered ultramafic complexes with chromite and titanomagnetite reefs and subordinate anorthosite layers. A few narrow belts and abundant enclaves of Sargur Group are rich in QCP suite, with the remaining lithological units scattered within the host gneisses. The Paleoarchaean gneissic complex and Sargur Group are overlain with a profound unconformity by Neoarchaean Dharwar Supergroup exposed in the prominent schist belts of Shimoga-Goa-Western Ghats-Bababudan and Chitradurga-Gadag, and in some smaller belts. There are three lithological sequences in Dharwar Supergroup viz., QPC (quartz-pebble-conglomerate) at the base, followed by quartzite-basalt alternations and BIF (Sequence-1); polymict conglomerate-wacke-pelite-quartzite-carbonate-manganese formation-BIF at basin margin (Vanivilas Subgroup), with the homotaxial pillow lava-pyroclastic (bimodal volcanics)-chert-BIF at the basin interior (Ingaldhal Volcanics) forming Sequence-2; and greywacke-phyllite-BIF-polymict conglomerate-volcanics forming the Ranibennur Subgroup (Sequence-3). Sequence-1 is named Bababudan Group, and Sequences 2 and 3 as Chitradurga Group. Tight to isoclinal folds are common and metamorphism ranges from greenschist to amphibolite facies of medium pressure type. The western margins are marked by basal unconformity and the eastern margins are tectonised. The age of Dharwar Supergroup is about 2600-2800 Ma. Isolated younger granites of 2600 Ma age (e.g. Chitradurga Granite) intrude the Dharwar sequence, as well as the Peninsular Gneiss (Arsikere, Banavara and Hosadurga granites). The EDC consists essentially of greenstone belts with pillowed basalts, pyroclastics and BIF in the middle, with a thin marginal QCP sequence occurring as ' screens' in the west, comprising quartzite, marble, pelite and manganese formation. Ultramafic schists are subordinate and layered complexes are uncommon. All along the eastern margin of most belts, felsic volcanics in association with polymict, volcanic conglomerates and minor BIF form a marker horizon. The greenstone belts are well-known gold belts of 2600-2700 Ma age. There are no basement-cover unconformities and the belts are intruded on all sides by voluminous younger granites of granodiorite-adamellite-tonalite-granite suite, resulting in low-pressure metamorphism. The younger granitic suite, correlated with global 'granite bloom' (Davis and Blecker, 1999), is dated at 2500-2600 Ma. Dharwar craton as a whole is characterised by progressive regional metamorphism of greenschist to granulite facies, from north to south, with isograds running E-W, orthogonal to the structural trendlines. All along the broad transition zone of amphibolite to granulite facies near the orthopyroxene isograd, called the Fermor Line, spectacular transformation of orthogneiss to incipient or arrested charnockite is seen, particularly in the classical stone quarries of Kabbaldurga. Similarly, but with the difference of concordance to the structural trendlines, a narrow transition zone of amphibolite to granulite facies is seen to the northeast in the Karimnagar granulite belt, and to the east in the Eastern Ghats granulite belt. Charnockite massifs occurring in the south represent the deeper sections of the Dharwar craton. Crustal scale shear zones separate the Dharwar craton from the Pan-African Pandyan mobile belt in the south, and the Grenvillean Eastern Ghats mobile belt in the east. Karimnagar granulite belt (~2500 Ma) exposes the deep crustal section of Dharwar craton. This granulite belt is tectonically juxtaposed against the Phanerozoic Godavari graben, with the Eastern Ghats mobile belt cutting across its Dharwar trend. The Archaean Dharwar craton therefore exposes a gently tilted crustal section towards the north and west that is dissected by boundary faults in the south, north and east during different times in the Proterozoic.

Plate tectonic models are increasingly being proposed for the evolution of Dharwar craton, especially with respect to the main schist belts. One of the most comprehensive models is by Chadwick et al (2000). This Andean model visualizes WDC as foreland with schist belts as marginal basins laid on a granitic crust. The EDC is regarded as an Archaean batholith that accreted on to the craton in the west along a diffuse zone of interaction. According to this model, Closepet Granite does not denote a distinctive younger pluton in the craton, but is part of the Dharwar batholith. The greenstone belts of EDC are considered as intra-arc basins. The NE to SW compression has resulted in top-to-SW thrusting and sinistral transpressive shearing at the margins of schist belts. The model visualizes oblique subduction towards WNW of the oceanic plate. The missing forearc accretionary prism and ophiolitic suture are not satisfactorily explained in this model. In contrast to this model, the French school (Chardon et al. 1996, 1998) has proposed a non-uniformitarian 'sagduction' model involving gravitational sinking of the greenstone pile, with tectonic slides at the margins. The EDC was probably caused by an underplated mafic magma or has originated from a mantle plume.

### *Bastar Craton*

Bastar craton consists largely of Archaean (2500-2600 Ma) and Palaeoproterozoic (2200-2400 Ma) granites containing islands of banded TTG gneisses, some of them preserving vestiges of ~3600 and 3000 Ma events. Ancient supracrustals consisting principally of QCP suite with BIF and minor basic-ultrabasic rocks, called Sukma Group in the south and Amgaon Group in the north, occur as scattered enclaves and narrow belts within gneisses and granites. The succeeding Bengpal Group occurs in an eastward-flaring, WNW-ESE trending belt from near Bailadila to Tulsi Dongar. Bengpal Group consists of a rare basal quartzite, overlain by alternations of metabasalts and andalusite schists. This succession is probably riftogenic. The sequence is profusely intruded by Archaean granites, and therefore Bengpal Group (2500-2600 Ma) is regarded as Neoarchaean in age. The Sukma and Bengpal Groups are characterized by low-pressure regional metamorphism that may be related to extensive granitic activity. The next event in the craton is the formation of Palaeoproterozoic BIF basins (Bailadila Group) that host rich iron ores feeding the Bhilai Steel Plant. The basins are formed in a long-lived N-S trending rift (Kotri rift) that developed into Kotri-Dongargarh orogen. Bailadila Group is deposited unconformably over the metabasalt-andalusite schist ensemble of Bengpal Group, as well as over the basement granites and gneisses containing Sukma/Amgaon enclaves. The Bailadila iron formation basins consist of basal quartzite, subgreywacke-pelite-tuff with polymict conglomerate interbeds and BIF, and therefore belong to 'Superior type'. The succeeding cycle comprises felsic to mafic volcanics and pyroclastics (Nandgaon Group) intruded by Dongargarh and Malanjkhand granites (~2300 Ma). Nandgaon Group is overlain unconformably by basalts alternating with sediments (Khairagarh Group). The next cycle in Kotri-Dongargarh orogen is Chilpi Group of greywacke-pelite-tuff interbedded with chert-limestone-manganese beds. Two parallel, but isolated and different type of belts, occurring to the east and west of Kotri-Dongargarh orogen are the Sonakhan and Sakoli belts. Sonakhan Group consists mainly of basic-acidic bimodal volcanics, BIF and greywacke-argillite suite with minor conglomerates. Sonakhan belt is sometimes described as a greenstone belt. This belt is intruded by ~2400 Ma old granites, and may correlate with Nandgaon Group. The triangular Sakoli belt, bounded by shear zones, is made of 80% metasediments, with subordinate volcanics, BIF, coticules, cherts and tourmalinites forming the remainder. Sakoli Group may be homotaxial with Chilpi Group. Chilpi and Sakoli Groups (~1800 Ma) are deflected parallel to the CITZ (Central Indian Tectonic Zone) during the Satpura orogeny. There are three granulite belts in the craton, viz. Bhopalpatnam, Bhandara-Balaghat and Kondagaon. Bhopalpatnam belt is situated on the rift shoulder of Godavari graben and is an exhumed belt of Mesoarchaean age corresponding to the Karimnagar granulite belt of Dharwar craton. Kondagaon belt is a horst-like narrow belt within the gneisses and may have been exhumed during Neoarchaean. The Balaghat-Bhandara belt is a boudin-type granulite belt formed and exhumed during the tectonic evolution of CITZ. Bastar craton is therefore a collage of volcano-sedimentary rift basins formed intermittently from Mesoarchaean to Palaeoproterozoic. Periodic exhumation of the craton brought up narrow granulite belts from mid-crustal depths. The craton was probably stabilized by ~1800 Ma, paving the way for deposition of flat-bedded Proterozoic ('Purana') sedimentary basins.

### *Singhbhum Craton*

Singhbhum craton consists of a core of Mesoarchaean multi-phase Singhbhum granite (3300 and 3100 Ma), having ~3500 Ma old vestiges. The granite is rimmed by supracrustal belts of varying ages. The main controversy relates to the iron formation basins (traditionally called as Iron Ore Group) rimming the Singhbhum granite. These were considered homotaxial earlier, but at least two iron ore cycles are recognized in recent years. The oldest event of the craton is reflected by the Older Metamorphic Group (OMG) occurring as enclaves within the Older Metamorphic Tonalite Gneiss (OMTG), both occurring near Champua and covering a time span of 3300-3400 Ma. The OMG consists of biotite-muscovite schist, fuchsite quartzite, ortho-, and para-amphibolite and BIF. Komatiite is conspicuous by its absence, which is surprising in such an older Archaean sequence. The iron formation basins of Gorumahisani (Badampahar Group) in the northeast and Daitari (Daitari Group) in the south are correlated with OMG and a train of enclaves is shown to link them. Alternatively, the iron formation basins (Badampahar, Daitari) may be younger than OMG. The dominant rock types of Badampahar/Daitari Groups are basic pillow lavas and pyroclastics, komatiites and BIF, with minor fuchsite quartzite and calc-silicate rocks. Quartzites are abundant in Daitari Group. These successions are intruded by Singhbhum granite in two major phases of 3300 and 3100 Ma. The older phase is trondhjemite-granodiorite and the dominant younger phase is granodiorite-adamellite-granite. The Bonai granite (3300 & 3100 Ma) and Kaptipada (Nilgiri) granite (3100 Ma) are correlatives of Singhbhum granite. The main iron ore basin occurring at the western margin of Singhbhum granite consists of polymict conglomerate, quartzite, shale, dolomite, chert, manganese formations and BIF belonging to Koira Group. The sequence overlies OMG and Singhbhum granite in the east, and Bonai granite in the west. Koira iron formation is comparable to the 'Superior type'. In the east, Singhbhum granite is unconformably overlain by the volcanic successions of Dhanjori and Simlipal Groups. These groups are surrounded by Mayurbhanj granite-granophyre that was earlier dated at ~2200 Ma (Rb-Sr), but recently dated at ~3000 Ma (Pb-Pb). The circular Simlipal basin consists of basal uraniferous QPC (quartz pebble conglomerate) and quartzite, overlain by three bands of tholeiitic metabasalts alternating with orthoquartzite, and intruded by the differentiated basic sill of Amjhor. A comparable, but more deformed succession is seen in the homotaxial Dhanjori basin situated to the north. The Dhanjori lavas are dated at ~2800 Ma (Pb-Pb & Sm-Nd). Isolated volcanic successions of Jagannathpur (2250 Ma, Pb-Pb) and Malangtoli unconformably overlie Singhbhum granite, and these were geologically correlated with Dhanjori and Simlipal volcanics. They have faulted contacts against the adjacent basins of Koira and Daitari. Another homotaxial volcanic suite (Ongarbira volcanics) occurring in a structural basin overlies the Koira basin.

In the northern arcuate boundary of Singhbhum granite occurs the Proterozoic North Singhbhum orogen. Recent dates suggest that the orogen may have been initiated in Mesoarchaean (~3000 Ma, Pb-Pb), but this idea (*see* Misra, 2006) needs to be confirmed by extensive studies. The orogen is divided into five domains from south to north. Overlying Singhbhum granite is the Dhanjori domain comprising a succession of polymict conglomerate, wacke, phyllite, quartzite, tuff and BIF, with ultramafic-mafic intrusions. The volcanic successions of Simlipal, Dhanjori, Ongarbira, Jagannathpur, Malangtoli etc form part of this domain. Dhanjori domain is followed by the Singhbhum shear zone. The shear zone consists of mylonitised granites ('soda granites') and phyllonitised basic volcanics, tuffs and siliceous phyllite. The next northerly domain of Ghatsila Group consists of mica schists, quartzites and felsic tuffs (Chaibasa Formation) overlain by greywacke-phyllite, quartzite, (Dhalbhum Formation). Ghatsila Group is overlain by Dalma volcanic belt that forms a major syncline trending E-W. Dalma belt consists of a lower unit of carbon phyllite, quartzite, volcanics and pyroclastics, and an upper unit of high-Mg basalts, komatiites and ultramafic tuffs, associated with pillowed tholeiitic basalts and tuffs. The Dalma lavas also yield dates of 2400 Ma (Pb-Pb) and 1600 Ma (Rb-Sr). The overlying Chandil domain consists of pelite, chert, carbonate and voluminous rhyolitic to dacitic ash flow tuffs. Chandil domain abuts against the Tamar-Poropahar shear zone that separates Singhbhum craton from Chhotanagpur Gneiss that forms the eastern extension of Satpura mobile belt. A younger succession (Gangpur and Kunjar Groups) of carbon phyllites, limestones and manganese silicate rocks, correlated with Sausar Group of CITZ, occurs within the North Singhbhum orogen. Another younger basin overlying the Singhbhum granite and other supracrustal sequences is called Kolhan Group that consists mainly of sandstones, shales and stromatolitic carbonates. Kolhan Group is correlated with the 'Purana' sequence by some authors. Several Proterozoic granites of various ages intrude the craton, the important bodies being Arkasani and related 'soda' granites (1600 Ma, Rb-Sr), Mayurbhanj granite-granophyre (2000 Ma Rb-Sr and 3000 Ma Pb-Pb), Kuilapal granite (1600 Ma, Rb-Sr; 2200 Ma Pb-Pb), Tamperkola granite (2800 Ma Pb-Pb), Bhuban granite (2800 Ma Pb-Pb) and Chakradharpur granite. A prominent mafic dyke swarm called the Newer Dolerite (2100 Ma, 1600 Ma K-Ar) marks the final stabilization of Singhbhum craton. Several plate tectonic models involving northward or southward subduction, intra-plate and ensialic orogeny, back arc basin and plume tectonics are proposed for the evolution of North Singhbhum orogen. Singhbhum craton is bounded by North Singhbhum orogen that abuts against Chhotanagpur Gneiss (Satpura mobile belt), and by Sukinda thrust against the Eastern Ghats mobile belt and partly abuts against the Bastar craton.

### *Bundelkhand Craton*

Bundelkhand craton is the northernmost craton of the Indian shield, which is concealed under the Indo-Gangetic Alluvium extending in the north up to the Himalaya, and bounded by Son-Narmada fault against the Satpura mobile belt in the south, and by the Great Boundary Fault against the Aravalli craton in the west. Bundelkhand craton has been compared to the Banded Gneissic Complex of Aravalli craton, from which it is separated by the Vindhyan basin and Hindoli belt along with their bounding faults. The craton is dominated by Bundelkhand granite (~80%), containing swathes of older gneisses and enclaves of ancient supracrustal rocks (20%). The gneisses are of TTG composition and have ages of 3300 Ma and 3100 Ma, with rare vestigial events of ~3500 Ma. Some of the enclaves are also of the similar age (~3300 Ma). The enclaves are distributed in two E-W trending tracts in the north and south. The northern tract from Babina to Karera consists of mafic-ultramafic rocks including pillowed basalts and basaltic komatiites, pelitic schists, banded calc-silicate rocks and BIF. Felsic volcanics of rhyolite-rhyodacite composition along with quartz and felspar porphyry also form an important unit of the central volcanic-plutonic complex. Recently, a structure resembling cauldron subsidence (Cole et al. 2005) is reported from Mohar (Jain et al. 2001). The outer periphery of the cauldron is circular with 7.5 km diameter and consists of granite breccia. Vindhyan sediments (Neoproterozoic) occupy the centre of the cauldron.

The southern tract from Madaura to Birar contains variably metamorphosed enclaves of peridotite, pyroxenite, serpentinite, metabasalt, tholeiitic amphibolite, limestone, fuchsite quartzite, biotite-garnet schist, phyllite and BIF. The enclaves and enclosing gneisses are deformed into three phases of isoclinal to reclined folds.

The 'granite bloom' of Bundelkhand craton is widely dated by Rb-Sr and U-Pb zircon methods at 2400-2500 Ma. Three main phases of granite are recognized viz. hornblende granodiorite, biotite granite with local rapakivi texture, and fine-grained leucogranite. The granite and granodiorite are metaluminous I-type and leucogranite is peraluminous S-type. The granite is riddled with quartz reefs containing pockets of pyrophyllite-diaspore and Pb-Zn-Cu ores. Hydrothermal quartz-sericite rocks and rhyolites are common in the granite. Porphyry dykes are also common. Mafic dyke swarms ranging in age from 1500 to 1800 Ma show extensive development. 'Purana' basins of Bijawar, Gwalior and Sonrai (~1800 Ma) and the great Vindhyan basin (>1600 Ma) complete the cratonisation of the region.

### *Aravalli Craton*

Aravalli craton is separated from Bundelkhand craton by the great Vindhyan basin and Hindoli Group that are bounded by faults. In the south, Son-Narmada Lineament and Central Indian Shear Zone swerve into Aravalli-Delhi orogen forming the extensions of Satpura mobile belt. Deccan Trap and Phanerozoic sediments conceal these extensions, especially along the regional, arcuate bend from Nagpur to Ahmedabad. With the Mahakoshal belt of CITZ extending west into Hindoli belt of Aravalli craton, the entire terrain from Great Boundary Fault to the Phulad Shear Zone in the west of Delhi fold belt may constitute the larger Satpura-Aravalli mobile belt, rather than being part of a craton. Unlike the CITZ and Chhotanagpur Gneiss regions of Satpura mobile belt, the Aravalli terrain exposes Archaean basement. The Aravalli craton is divided into an eastern Mewar craton and western Marwar craton separated by Phulad Lineament. Mewar craton consists of Mewar Gneiss, Mangalwar-Sandmata complexes with Pb-Zn belts, Hindoli belt and Aravalli-Delhi orogen.

*Mewar craton:* Banded Gneissic Complex consists of three major components, viz., (i) Mewar Gneiss with ancient supracrustals of Jagat Group (ii) Mangalwar Complex to the north of Nathdwara fault, and (iii) Sandmata Complex as the transitional granulite facies variant of Mangalwar Complex. Mewar Gneiss is an essentially TTG gneiss (3300-2900 Ma) that forms basement to the Aravalli Supergroup. It also includes granite plutons such as the Untala and Gingla (~2900 Ma), as well as inliers within the fold belt like the Sarara and Mondo. The supracrustal enclaves of Jagat Group are seen within Mewar Gneiss that has still older (~3500 Ma) components. The enclaves are amphibolites, quartzites, marbles, mica schists and BIF. Ultramafic schists, some of them of komatiitic composition are also seen in the enclave suite. A suite of 'primary' greenstones (Sawadri Group) and 'secondary' greenstones (Tanwan Group) is recorded within the gneisses and migmatites of Ran Complex (equivalent of Mangalwar-Sandmata Complex), but their stratigraphic status is controversial, because some authors consider them as strike extensions of Aravalli belt and correlate them with Aravalli Supergroup. Mangalwar Complex consists essentially of migmatitic gneisses with dominant enclaves of pelitic schist and gneiss, and subordinate calc-silicate rock, amphibolite, tremolite-talc-chlorite schist and quartzite, as best exposed near Bhilwara. The age of Mangalwar Complex is not well constrained, but may be bracketed at 2500-2800 Ma, with the upper limit fixed by the intrusive Berach granite. Sandmata Complex is a higher-grade equivalent of Mangalwar Complex, containing slices of charnockites and enderbites tectonically exhumed from deep crust. The exhumation may be related to the Aravalli orogeny at 1700-1900 Ma. A series of isolated metasedimentary belts rich in Pb-Zn mineralisation unconformably overlies Mangalwar Complex. These belts are correlated with the middle part (Udaipur Group) of Aravalli Supergroup. Hindoli Group fringing Vindhyan basin comprises turbiditic greywacke-phyllite suite, with minor quartzite, algal dolomite and tholeiitic basalt, felsic volcanics and pyroclasts. Zircons from rhyodacite yield concordia age of ~1850 Ma, making it coeval with parts of Aravalli Supergroup.

Aravalli fold belt extends from near Nathdwara towards the south and finally swerves eastward into CITZ beneath the Phanerozoic cover The four-fold succession of the belt called Aravalli Supergroup starts with Delwara Group at the base, marked by basal conglomerate and arkose, overlain by a thick horizon of amygdular metabasalts with thin interbeds of dolomite and BIF. Prominent unconformity between the basement of Mewar Gneiss and Aravalli sequence is exposed between Nathdwara and Salumbar. Meta-arkose, palaeosol and quartz pebble conglomerate mark this profound unconformity. Delwara Group is overlain by Debari Group comprising polymict conglomerate, arkose, dolomite, chert, manganiferous phyllite, quartzite and stromatolitic phosphorite. This is followed by Udaipur Group consisting of proximal greywacke-phyllite association with pebbly conglomerate, dolomite with Pb-Zn mineralisation and phyllite-quartzite suite. The shallow water succession is followed upward by the deep-sea sequence of distal turbidites (Jharol Group). The interface between the shallow-water and deep-water facies is marked by Rikhabdev ultramafic belt comprising serpentinites and talc-carbonate rocks that are interpreted as ophiolites. The overlying unit of quartzite and phyllite

(Lunavada Group) is believed to mark molasse sedimentation. The isolated Champaner Group consisting of subgreywacke, quartzite, dolomite and manganiferous phyllite, is intruded by the younger Godhra granite that is dated at 750 Ma. Champaner Group is placed at the topmost part of Aravalli Supergroup. The Aravalli sedimentation commenced in a continental margin rift at about 2200 Ma, followed by deformation, metamorphism and granite intrusion by 1700 to 1900 Ma.

Delhi fold belt is in tectonic-cum-unconformable contact with Aravalli fold belt, and is divisible into North Delhi Fold Belt (NDFB) and South Delhi Fold Belt (SDFB). NDFB occurs in three sub-basins, viz, Bayana-Lalsot basin, Alwar basin and Khetri basin. Khetri basin forms the northern strike extension of the main Delhi fold belt that includes the SDFB, and is further sub-divided into North and South Khetri basins. Delhi sedimentation has occurred in several isolated, but interlinked sub-basins showing diachronous development. NDFB consists of three groups viz, Raialo Group, Alwar Group and Ajabgarh Group. Raialo Group starts with basal conglomerate, overlain by tholeiitic basalts with sedimentary interbeds in Bayana basin, and by marbles and bimodal volcanics in Alwar basin. The overlying Alwar Group is largely arenaceous in all sub-basins and contains mainly conglomerates and quartzites. The succeeding Ajabgarh Group is mainly argillaceous and contains carbonaceous phyllite and ferruginous sandstone. In Alwar basin, Ajabgarh Group starts with carbonates, phosphorites and basic volcanics before the onset of the main pelitic sedimentation. Copper mineralisation is important in Khetri basin, and Kho Dariba area of Alwar basin. Saladipura pyrite deposit is seen in Khetri basin. Many granitic bodies intruding NDFB have Rb-Sr ages of 1450 to 1650 Ma. Kishengarh nepheline syenite (~1500 Ma) intrudes as a diapiric pluton into pre-Delhi (and probably Aravalli) sequence near Ajmer. Since the basement gneisses and granites are about 1850 Ma old, the age of NDFB may be between 1450 and 1700 Ma.

SDFB exposes a continuous succession from Ajmer in the north to Himmatnagar in Gujarat. It comprises two sub-basins, the eastern Rajgarh-Bhim basin and the western Barotiya-Sendra basin, separated by median gneiss at Beawar. Several parallel strike faults disrupt the succession with the result only tectono-stratigraphic units are recognizable. There are several enclave suites within the surrounding gneisses (Gogunda and Devgarh Groups, Ras Marble and Ajmer Formation) whose stratigraphic position is debatable. Rajgarh-Bhim basin contains arenite-carbonate-pelite sequence (Rajgarh and Bhim Groups) indicating shelf to slope environment. Barotiya-Sendra basin is made of dominant bimodal volcanics (Basantgarh, Barotiya and Sendra Groups) suggestive of oceanic setting. Shear zones separate the groups containing different depositional sequences, e.g., Rajgarh Group is continental slope sequence; Bhim Group is arc-trench gap sequence; Sendra Group is volcanic arc sequence; Barotiya Group is marginal sea sequence; and Basantgarh Group is an arc-trench sequence juxtaposed against Phulad Ophiolite. The ophiolite suite consists of dismembered bodies of epidiorite, amphibolite, metagabbro, norite, serpentinite and tonalite-granodiorite-plagiogranite. The ophiolite is reported to contain blue schist facies assemblages, and has an age of around 1000-1100 Ma. In the north, the schists show high-grade Barrovian metamorphism culminating in granulite facies as seen in the Pilwa-Chinwali granulite boudins dated at 1430 Ma. Similar high-grade rocks are seen to the south in Balaram-Abu Road and Deri-Ambaji areas. SDFB is intruded extensively by Sendra-Ambaji granite suite (~1100 Ma). Newania carbonatite (~1000 Ma) of Delhi age intrudes the Archaean Untala granite. The evolution of SDFB is bracketed between 900 and 1100 Ma.

*Marwar craton* represents the terrain situated to the west of Phulad Lineament, and is traditionally included under Aravalli craton. The craton has a substrate of unclassified gneisses with QCP enclaves, but it is covered for the most part by younger successions. Neoproterozoic supracrustal belts of Sirohi, Sindreth and Punagarh occur to the west of Phulad Lineament, and these belts are interpreted as successor basins of Delhi orogeny. Sirohi Group is made of QCP suite, Sindreth Group (750-770 Ma) is largely arenaceous with felsic to mafic volcanics, and Punagarh Group is a QCP association with mafic volcanics. Erinpura batholith and associated tungsten bearing granites (Balda, Degana), Godhra granite intruding the Champaner Group, and linear albitite bodies intruding Khetri belt represent widespread post-Delhi magmatism (700-800 Ma).

Malani Igneous Suite (MIS) of Marwar craton is the largest felsic volcanic province of India. It represents A-type, within-plate magmatism of Neoproterozoic age (680-780 Ma) that unconformably overlies the successor basins (Sirohi etc.) of Delhi orogeny. MIS consists of bimodal volcanics with a dominant felsic component, granitic ring intrusions (Jalor, Siwana, Tusham etc.) and radial dykes. Felsic volcanics are mainly rhyolite, perlite and trachyte, associated with welded tuff and explosion breccia. MIS is visualized either as product of basaltic underplating or due to hot spot or mantle plume activity.

Malani magmatism is succeeded by the deposition of sediments of Marwar Supergroup during late Neoproterozoic to Eocambrian. The unfossiliferous sediments are deposited in the undeformed and unmetamorphosed basins of Nagaur and Birmania, together with their isolated sub-basins. The NNE trending basins have a westerly tilt and extend into the Salt Range of Pakistan. Marwar Supergroup consists of arenaceous sediments (Jodhpur Group) at the base, followed by an evaporite sequence (Hanseran Group) that is homotaxial with Bilara Group of stromatolitic dolomites, and an upper sequence of argillites (Nagaur Group). Marwar basins are well known for their potash bearing halite, and gypsum deposits. The complete stabilization of Marwar craton in Eocambrian, is followed later by the outpouring of end-Cretaceous Deccan flood basalts, associated with intrusion of alkaline rocks and carbonatites (Mundwara, Sarnu-Dandali etc.) and lamprophyric dykes.

The post-Archaean (post-Mewar Gneiss and Mangalwar Complex) evolution of the craton is characterized by the operation of Proterozoic Wilson cycles. The Aravalli basin began as a continental rift that opened into deep ocean, which was closed by easterly subduction, leaving Rikhabdev ophiolite as the oceanic remnant around 1800 Ma, concomitantly with exhumation of granulites (Sandmata Complex). The tensional regime of Aravalli rifts saw the development of the parallel Hindoli rift basin (~1850 Ma) between the Bundelkhand and Aravalli cratons. Hindoli sediments are similar to the lower and middle part of Aravalli succession. The pull-apart basins that opened contemporaneously with Aravalli rift on the basement of Mangalwar Complex contained significant SEDEX-type Pb-Zn mineralisation. These pull-apart basins are penecontemporaneous with Udaipur Group of the Aravalli sequence. The tensional regime following the Aravalli suturing saw the development of several grabens of NDFB. Their development was aborted by 1450 Ma. The SDFB evolved later as a Red Sea type rift on Mewar craton and progressed towards westerly subduction, island arc volcanism and ocean closure marked by Phulad Ophiolite and granulite exhumation (Pilwa-Chinwali and Balaram-Abu). During the long period of crustal stability in Marwar craton, successor basins (Sirohi, Sindreth and Punagarh) were involved in basin inversion and granitic magmatism (Erinpura granite, 730-830 Ma). Precambrian cratonisation was accomplished with the advent of Marwar basins containing stable QCP suite with significant evaporites forming valuable deposits of potash and gypsum.

## Mobile Belts

### *Eastern Ghats Mobile Belt* (EGMB)

EGMB is a NE trending belt about 1000 km long and 300 km wide at the maximum, and tapers from north to south. It cuts across the trendlines of Dharwar, Bastar and Singhbhum cratons, with a transitional metamorphic boundary in the west. The eastern boundary of the mobile belt is concealed under the Phanerozoic sediments of the East Coast of India, and therefore its dismembered portions may be traced in the adjoining Gondwanic continents of Antarctica or Australia. Granulite facies rocks consisting of charnockites, Khondalite Group (QCP suite) and leptynites dominate the mobile belt. Local UHT (ultra high temperature) metamorphism marked by cordierite-sillimanite-hypersthene-sapphirine-spinel-garnet assemblages is significant for regional correlation and tectonic evolution of the belt. Alkaline plutons with nepheline syenite as an important constituent occur close to the craton-mobile belt margins in the west and north. Layered anorthosite complexes are found in the south and massive anorthosite bodies in the north. Vast resources of bauxite cap the high hills of Eastern Ghats. The mobile belt is the provenance for the thorium and titanium rich placers of the East Coast.

The mobile belt is broadly divisible into four longitudinal zones, viz, Western Charnockite Zone (WCZ), Western Khondalite Zone (WKZ), Central Migmatite Zone (CMZ) and Eastern Khondalite Zone (EKZ). The WCZ represents the exhumed deeper parts of the craton, and has a transitional boundary with the craton, known as Eastern Ghats 'front' that marks the marginal zone of the mobile belt. The mobile belt *sensu stricto* is represented by the WKZ, CMZ and EKZ, and is separated from WCZ of the cratonic margin by a shear zone all along the contact, known locally from south to north as Sileru, Machkund and Sukinda shear zones. These longitudinal zones have been modified by some authors into different domains and provinces based on the data from isotopic mapping and satellite imagery, but a consensus is yet to emerge due to the limited database. The longitudinal zonation conforming to regional structural trends indicates that EGMB does not extend along the strike in the south to the E-W trending Pandyan mobile belt (PMB) or the Southern Granulite Terrain (SGT), thereby negating the traditional view of their contiguity.

The marginal zone between EGMB and Dharwar craton is demarcated *on the cratonic side* by the thrust at the eastern margin of Cuddapah and Pranhita-Godavari basins and extends for a short distance along the western boundary of Nellore schist belt, to be finally lost under the coastal sediments near Chennai. Nellore schist belt, occurring within the marginal zone, consists mainly of amphibolite and metabasalt, quartzite, Barrovian-type metamorphic pelitic schists, carbonate rocks, felsic tuff and barite, and has a low-grade western part and high-grade, migmatitic eastern part. The belt is intruded by Kandra Igneous Complex that is interpreted as an ophiolite, and has a mélange zone near Kanegiri. Nellore schist belt, originally interpreted as an Archaean greenstone belt of EDC, is now known to be part of the marginal zone of EGMB. It is a Proterozoic schist belt that extends to the north as Khammam schist belt. Nellore schist belt is dated (U-Pb zircon age of felsic volcanics) at 1800-1900 Ma, with indications of some older ages of ~2200 Ma. In Khammam area, the EGMB has NE trend that truncates the NW trend of the Archaean Karimnagar granulite belt along the Cuddapah boundary thrust. Layered anorthosite-gabbro complex of Chimalpahad containing chromite lenses in pyroxenites intrudes the Khammam schist belt. The Prakasam alkaline province consisting of numerous alkaline plutons (Elchuru, Purimetla, Uppalapadu, Settupalle, Podili etc) is emplaced in the gneisses of the marginal zone. The marginal zone with Bastar craton is marked by amphibolite-granulite facies transition, with local development of incipient charnockite in Jeypur area. In Khariar area to the north, WCZ is not well developed and so the WKZ occurs at the marginal zone bounded by Lakhna thrust that is the continuation of Machkund shear zone. The marginal zone with the northern part of Bastar craton and southern part of Singhbhum craton is involved in a series of faults causing confusion in the demarcation of rock suites of the craton and mobile belt. The marginal zone with Bastar and Singhbhum cratons is also characterized by the presence of alkali plutons such as Kunavaram, Kunduluru, Khariar, Bhela-Rajna, Redhakhol (Rairakhol) and Kankrakhol.

Western Charnockite Zone of the cratonic margin extends from Ongole through Jeypur to Riamal. Generally, the zone consists of charnockites and enderbites with minor mafic granulites. In Ongole sector, layered basic complexes of Kondapalle and Chimakurti (with chromite layers in pyroxenite) have caused UHT metamorphism (1100° C at 8 kb) in the surrounding Mg-Al pelites. Charnockites indicate Archaean (~2800 Ma) protolith ages overprinted by the regional event of 1500-1700 Ma from various sectors, denoting the initiation of EGMB at the continental margins and 'Purana' basins in the cratonic interior. Western and Eastern Khondalite Zones are dominated by garnet-sillimanite-graphite gneisses, sapphirine-spinel rocks and other Mg-Al pelites, with subordinate quartzites, calc-silicate rocks, rare marbles and manganiferous silicate rocks, belonging to Khondalite Group. Garnet-sillimanite gneisses and Mg-Al rocks have protolith composition of greywacke-pelite suite. Leptynites also abound, but charnockites and basic granulites are subordinate. UHT metamorphism (~1000° C at 8-9 kb) is also reported locally. Massive anorthosite bodies are emplaced within Khondalite Group, the prominent ones being the Bolangir massif, and those of Chilka Lake, Turkel and Jugsaipatna. Gneisses and charnockites of these zones yield Rb-Sr and U-Pb ages of 1400-1500 Ma. Impress of widespread regional metamorphism at ~1100 Ma is also recorded. Anorthosite massifs are dated at 800-900 Ma. Central Migmatite Zone is sandwiched between the two Khondalite Zones. CMZ consists of leptynites and migmatitic gneisses with subordinate charnockites, basic granulites and Khondalite Group. Widespread Rb-Sr and U-Pb zircon ages of 950-1100 Ma mark the peak of Eastern Ghats orogeny, involving widespread high-grade metamorphism and crustal anatexis, producing extensive migmatites in CMZ.

The EGMB represents a classic Proterozoic example of Pacific accretionary to Himalayan collisional orogen. The mobile belt comprising WKZ, EKZ and the median CMZ, together with its cratonic basement of WCZ and the marginal zone, has been thrust towards the west with top-to-west movement, because of compression from the Enderby Land of East Antarctica. Rifting commenced about 1400 Ma in the north and about 1250-1350 Ma in the south, with the emplacement of alkaline complexes that were deformed into nepheline gneisses. This was followed by the deposition QCP suite at the continental margin and greywacke-pelite suite in deeper parts. Deformation, metamorphism and granitic magmatism culminated in Eastern Ghats orogeny at 950-1100 Ma. This is followed by the emplacement of massive anorthosite plutons and garnetiferous S-type granites at 800-900 Ma, leading to crustal stabilization in Neoproterozoic. Later impress of Pan African 500-800 Ma activity is seen in some sectors in the form of mineral ages.

### *Pandyan Mobile Belt* (PMB)

PMB refers to the granulite terrain situated to the south of Palghat-Cauvery shear zone (PCSZ). It is also known as the Southern Granulite Terrain (SGT), but the terminology is ambiguous because the granulite terrain of south India covers the entire region to the south of Fermor Line. Further, SGT is defined in different ways by various authors leading to semantic confusion. The granulite terrain of south India includes the cratonic charnockites of Dharwar craton (Coorg, BR Hills, Javadi, Chitteri, Kallarayan and Shevaroy) and mobile belt charnockites (Kodaikanal, Cardamom, Varushanad and Nagercoil) of Pandyan mobile belt. The granulite belt of Dharwar craton is characterized by the greenstone ensemble of mafic-ultramafic rocks and BIF, shows low- and medium-pressure metamorphism, preserves Dharwar trendlines, contains TTG gneisses transforming to enderbites, and shows widespread Archaean ages (2500-2600 Ma) by multichronometric methods. The granulites of the mobile belt, on the other hand, are characterized by QCP suite, show dominantly low-pressure metamorphism, have E-W trendlines athwart the Dharwar trend, contain GAG suite transforming into granitic charnockites, and show widespread Pan-African ages (550 to 750 Ma) by multiple isotopic dating. The Pan-African granulite terrain is therefore called the Pandyan mobile belt in preference to the diffuse terminology of SGT.

The PMB is divided from north to south into the Marginal Zone, Madurai Block and Trivandrum Block, separated by major shear zones. The Marginal Zone is separated from the cratonic granulite belt by the Moyar-Bhavani-Attur shear zone (MBASZ). The *Marginal Zone* extends in the south up to the mobile belt boundary *sensu stricto* at PCSZ. North of the MBASZ, there is transition from amphibolite to granulite facies of the craton, and although contiguous, this granulite zone is not included in the Marginal Zone of the mobile belt. This is because the Marginal Zone preserves the elements of both the craton and the mobile belt, whereas the transition zone contains only cratonic elements.

The cratonic elements of the Marginal Zone are layered Bhavani gneisses containing mafic-ultramafic rocks, BIF, fuchsite-kyanite quartzite, pelitic schist and calc-silicate rock of cratonic Sargur and Dharwar as well as Vengad belts. Charnockite massifs of Nilagiri, Kollimalai, Pachaimalai and Wayanad form part of the Marginal Zone. The Archaean (~2900 Ma) layered basic complexes of Sittampundi and Bhavani (Mettupalayam) intrude the rocks of Marginal Zone. The mobile belt elements of the Marginal Zone are the Pan-African granites of Sankari, Punjaipuliyampatti, Marudamalai and Karamadai. The ~600 Ma old Pan African Sankari granite has enclaves of marble, calc-silicate rock and quartzite (Khondalite Group). The *Madurai Block* is bounded by PCSZ in the north and Achankovil shear zone (AKSZ) in the south. It consists essentially of pink granitic gneisses, charnockites and large swathes of QCP suite described as Khondalite Group, but these are not homotaxial with that of EGMB. The main lithotypes are quartzites, garnet-sillimanite-graphite gneisses, calc-silicate granulites, crystalline limestones supporting cement factories and Mg-Al pelitic gneisses containing cordierite-sillimanite-spinel-hypersthene-sapphirine assemblages. The *Trivandrum Block,* also called the Kerala-Khondalite Belt, is also made of similar supracrustal association, but occurs in a thick straight belt, unlike the swirling patterns of Madurai Block. Charnockites of Nagercoil Sub-block are also conspicuous in Trivandrum Block. Incipient charnockite formation is well known from the whole of Pandyan mobile belt, the important areas being Palghat Gap in the Marginal Zone, Melur and Pudukkottai in Madurai Block, and several areas around Trivandrum in Trivandrum Block. Massive anorthosites, characteristic of Proterozoic mobile belts, are emplaced at Kadavur, Oddanchatram and Perinthatta. The PMB contains several intrusions of syenite and granites of Pan-African age, the important bodies being Sivamalai and Puttetti syenites, and Munnar, Chengannur and Pariyaram granites. Extensive thermobarometric studies in PMB have indicated clockwise ITD path resulting from collision, followed by a later cooling path. Vestiges of earlier Palaeoproterozoic events (1700-1800 Ma) are preserved in the rocks, but the main orogeny is Pan-African (500-600 Ma). The collisional orogeny responsible for generation of PMB probably involved the Congo, Kalahari or Tanzanian craton in the south that collided with Dharwar craton in the north.

Recently, a V-shaped Neoproterozoic shear zone called the Karur-Kambam-Painavu-Trichur Shear Zone (KKPTSZ) has been identified in the SGT, largely based on isotopic mapping and satellite imagery interpretation. This shear zone, rather than the PCSZ, is believed to divide the Archaean Dharwar craton from the SGT. The SGT occurring to the south of KKPTSZ is regarded as the southern extension of the Mesoproterozoic EGMB (Ghosh et al 2004). This radical viewpoint needs confirmation by detailed field studies to establish the ground truth, since the geology on either side of the shear zone is apparently similar.

*Satpura Mobile Belt* (SMB)

Satpura mobile belt is a very long E-W trending orogenic belt that cuts across the northern part of Peninsular India. The mobile belt divides the Indian shield into northern Bundelkhand protocontinent and the southern Deccan protocontinent. The belt is divided into four sectors along its strike from west to east, viz., (i) Aravalli craton with its Aravalli-Delhi orogen, (ii) Central Indian Tectonic Zone or CITZ, (iii) Chhotanagpur Gneiss with North Singhbhum Orogen (NSO), and (iv) Meghalaya Plateau of North-East India. The CITZ is the most extensively studied sector of the mobile belt. CITZ is also the Satpura mobile belt *sensu stricto*, and therefore will be used as the type area for comparison with its eastern and western extensions.

The *CITZ* is bounded by the Son-Narmada North Fault (SNNF) in the north that abuts against the Vindhyan basin situated to the south of Bundelkhand granite. In the south, CITZ is bounded by the Central Indian Shear Zone (CISZ) that abuts against Bastar craton. Mahakoshal supracrustal belt occurs in the northern part of CITZ between the SNNF and SNSF (Son-Narmada South Fault). This belt consists of three formations starting with basal quartzite resting unconformably on the gneissic basement. This is followed by a succession of stromatolitic carbonate, BIF, phyllite, pillowed tholeiitic basalt, manganoan chert, BIF and ultramafic plugs. The overlying greywacke-argillite suite with basal polymict conglomerate and alternations of BIF and phyllite complete the sequence. Mahakoshal belt is deformed and metamorphosed in low-pressure greenschist facies. It is intruded by granites on both sides (Barambaba, Jhirgadandi and Madanmahal) that have Rb-Sr ages of 1600-1700 Ma. Minor intrusions of syenites, carbonatites, alkali gabbros, lamprophyres and barite veins are also noticed. The syenites and gabbros are dated at 1600-1800 Ma. The basin evolved as a pericratonic rift that is intruded by granites of magmatic arc and so may be a back-arc rift that deepened from north to the south. Boudin-type Makrohar granulites, exhumed by orogenic deformation, occur to the south of SNSF. Mahakoshal belt does not extend in the east beyond Rihand Dam, and links up after long gap of cover rocks with the Hindoli belt of Aravalli craton in the west. Both belts are called loosely as greenstone belts, but such a label may be misleading to the general reader. *Betul supracrustal belt* occurs in the south between the Mahakoshal and Sausar belts, within gneisses dated at 1500 Ma. It is separated from Mahakoshal belt by the Balarampur Fault and from Sausar belt by the Tan Shear Zone, and is dissected by faults and covered by Gondwana sediments and Deccan Trap.

Pb-Zn mineralisation is reported from the Betul belt. The belt exposes Betul Supergroup that consists of magnesian schists, garnet-staurolite-biotite-graphite schists and calc-silicate rocks (Golighat Group), overlain by pillowed metabasalts, felsic volcanics and pyroclasts, and pyritous cherts (Bargaon Group) and is succeeded by a younger sequence (Bhopali Group) of dolomite, calc-silicate rock, quartzite and metabasalts. The succession is intruded by layered mafic intrusion of gabbro-pyroxenite-diorite (named after Padhar or Gajpur), and by granite (850 Ma). Betul belt may represent a magmatic arc with intra-arc sedimentary belts. The belt is comparable to the Bhilwara Group with Pb-Zn belts in the Mangalwar Complex of Aravalli craton in the west, and to the Bihar mica belt and the Hesathu-Belbathan mineralized belt of Chhotanagpur Gneiss in the east. The arcuate *Sausar supracrustal belt* occurs between Tan Shear Zone and the CISZ. It is surrounded by Tirodi gneiss and bounded by boudin-type granulite belts of Ramakona-Katangi in the north and Bhandara-Balaghat in the south. The Sausar belt is well known for its rich manganese mineralisation. The belt consists of two major cycles of quartzite-marble-pelite that are involved in imbricate thrusting and complex folding. Sausar belt is metamorphosed in 'migmatitic' amphibolite facies of Barrovian type. There are Archaean imprints in the Bhandara-Balaghat granulites, but two major metamorphic events at 1500-1600 Ma and 1000-1100 Ma are conspicuous in the surrounding Tirodi gneiss and the gneisses of Tan Shear Zone. The Sausar belt may be correlated with Lunavada-Champaner (upper Aravalli)-Delhi sequence in the west and with the Ranchi, Gangpur and Kunjar Groups in the east. There are two models of evolution of CITZ. One model visualises the southerly subduction of Bundelkhand craton, along with its supracrustal belts, below the Bastar craton to produce the Kotri-Dongargarh orogen and the back arc rift of Mahakoshal and allied belts of CITZ. A variant of this model is the presence of two subduction zones, viz the Mahakoshal in the west, and Singhbhum in the east with the intervening Chhotanagpur Gneiss as the arc batholith. Another model visualises northerly subduction of Bastar craton below the Bundelkhand craton, with Betul and Mahakoshal belt forming back-arc fold-thrust belts, followed by accretion of the cratons during 1500 Ma along the Ramkona-Katangi granulite belt marking the suture. Sausar belt formed after the amalgamation of the cratons, and it was closed during 1100 Ma by continued thrusting propagating from CISZ. The details of geology of Aravalli craton have been summarized in the foregoing account (p.57-61) and will not be repeated here.

*Chhotanagpur Gneiss* is an E-W trending terrain consisting of a variety of gneisses and younger granites, narrow trains of supracrustal enclaves, discontinuous boudin-type granulite belts, and major parallel shear zones. It is comparable to CITZ in many ways. The succession to the north of Bihar mica belt is called Munger Group that is exposed in Rajgir Hills near Gaya and Kharagpur Hills near Bhagalpur. They are mainly made of quartzites, phyllites and para-amphibolites. They were earlier correlated with Mahakoshal Group, but since the lithological association is different and Mahakoshal belt does not appear to extend beyond Rihand Dam, Munger Group may be correlated with Bijawar Group. Betul belt is correlated with Bihar mica belt and Hesathu-Belbathan belt of CGC and with Mangalwar Complex of Mewar craton. Tan Shear Zone corresponds to the North Purulia Shear Zone. Sausar belt correlates with the Gangpur and Kunjar Groups of NSO and Ranchi belt of CGC. Ramakona-Katangi granulite belt correlates with Hazaribagh-Dumka granulite belt. CISZ connects with Tamar-Poropahar (South Purulia) shear zone. A group of intrusions of anorthosite-gabbro, norite and dolerite intrude the Chhotanagpur Gneiss. Anorthosite-gabbro bodies are seen in Bela near Gaya, Gopalpur in Bihar mica belt, Dumka near Hazaribagh, and Bankura and Saltora (Bengal anorthosite) in Purulia belt. Some dolerite dykes are coronites containing coronas of olivine around plagioclase and garnet encircling pyroxene.

In *North-East India*, Shillong (Meghalaya) plateau and adjacent areas expose Precambrian rocks that can be extrapolated to be in strike continuity with Chhotanagpur Gneiss, but for the possible N-S offset caused by Rajmahal volcanics. The Shillong Plateau consists of gneisses with high-grade supracrustal enclaves and boudin-type granulites, Proterozoic Shillong Group of less deformed QPC sediments intruded by Khasi 'Greenstone', and younger Pan-African granites. The geological setting is comparable to gneisses of Bihar mica belt and Hazaribagh-Dumka granulite belt.

The correlation of the various units of Meghalaya Plateau, Chhotanagpur Gneiss (including North Singhbhum Orogen) and CITZ is only tentative because of lack of physical continuity of the various elements due to large intervening areas of Phanerozoic cover, presence of numerous shear zones and significant lateral facies change.

### *Precambrian of Himalaya*

The Himalaya represents a large, NW to NE trending arcuate orogenic belt with convexity to the south, and extends for a length of 2500 km and width of 300-400 km from Nanga Parbat syntaxis in the west to Namche Barwa syntaxis in the east. It is geologically divisible into six longitudinal zones of which the Lesser Himalaya and Higher Himalaya comprise Precambrian rocks. The Lesser Himalaya is separated from the underlying Siwalik Zone by the Main Boundary Thrust (MBT) and from the Higher Himalaya by the Main Central Thrust (MCT). The Higher Himalaya is separated from the overlying Tethyan Zone by the Trans-Himadri Thrust. The ubiquitous thrusts producing nappes and klippen have locally caused inverted metamorphic zonation. The longitudinal zones are further divided into three main geographic regions of Western, Central and Eastern Himalaya. The tectono-stratigraphy of Himalaya is classified into eleven sedimentary cycles of which the First to Fourth Cycles (Cycle I to IV) pertain to Precambrian. The *First Cycle* consists of QCP suite, metamorphosed from greenschist to upper amphibolite facies of Barrovian type. These sediments are enclosed as rafts and lenses within banded quartzo-felspathic gneisses called the Central Crystallines in Higher Himalaya. They are dated at 1800-2000 Ma from different locations. They are generally called as crystallines with prefixes of different local names such as Nanga Parbat, Tso Morari (in Trans Himalaya), Suru, Rohtang, Darjeeling and Kanchenjunga in Higher Himalaya. Mg-Al pelites are known from Nanga Parbat, and eclogite lenses showing UHP (ultra-high pressure) metamorphism from Tso Morari. Extensive development of Pan-African granites (580 Ma) is seen within Rohtang crystallines. Tertiary (14-28 Ma) leucogranites are also recorded. In Uttarakhand, the Central Crystallines are called the Vaikrita Group, in Nepal as Himal Group and in Arunachal Pradesh as Se La Group. In Lesser Himalaya, the basement complexes are exposed in thrust sheets and windows, e.g., Kishtwar window of Kashmir (Sincha Formation), Rampur-Larji windows, and Almora, Baijnath and Ascot thrust sheets in Himachal Pradesh (Kullu Group), Annapurna gneiss in Nepal and Lingtse gneiss in Darjeeling. The *Second Cycle* starts with orthoquartzite-metabasalt association passing into quartzite-carbonate facies and ending up with quartzite-slate unit. Lateral facies changes, interdigitation of formations and interruption by thrusting are common. Stromatolitic carbonates and phosphorite are also common. Metalliferous mineralisation is seen locally. In the Higher Himalaya of Kashmir, these are called Bafliaz, Chandinar and Buniyar Formations and Kalamund Quartzite. In Darjeeling, Sikkim and Bhutan, these are called Jaishudanda Formation. In Lesser Himalaya of Jammu, they are called Jammu or Riasi Limestone. The Second Cycle is best developed in Himachal Pradesh within the crystalline nappes of Larji, Shali and Deoban. In Larji window, the cycle is represented by the older Rampur Group and younger Larji Group. The Shali window exposes Sundernagar Group with Mandi Volcanics and Shali Group. Mandi Volcanics are tholeiitic basalts and andesites. Shali Group contains interbeds of salt and marl called *lokhan*. In Deoban window, the succession is named as the lower Dharagarh Group ('Chakratha Series') and the upper Deoban Group. In Uttarakhand, the cycle is known by different local names (Garhwal, Pithoragarh, Rautgara etc). In Nepal and Bhutan, the second cycle is not distinguished separately. In Darjeeling-Sikkim, the cycle is called Daling Group, and in Arunachal Pradesh, it is known as Bomdila Group.

The *Third Cycle* comprises basal conglomerate, arenite, pelite and stromatolitic carbonate. The cycle ends with the thick regressive sequence of quartzite and quartz pebble conglomerate. The presence of evaporites, particularly gypsum, is characteristic. Volcanism is nearly absent. In the Higher Himalaya of Kashmir, the Third Cycle is represented by Salkhala Group. It is intruded by end-Neoproterozoic to early Palaeozoic (450-550 Ma) granites (Dalhousie, Mandi etc). The overlying Kulu Group is known as Haimanta Group in Uttarakhand. This cycle is seen in the highest allochthon of Himachal Pradesh and is called Jutogh Group. In the Lesser Himalaya of Himachal Pradesh and Uttarakhand, this cycle is called Simla ('Simla Slate') and Jaunsar Groups and as Hazara Group to the west of Kashmir syntaxis. The equivalents of Third Cycle in Eastern Himalaya are Nawakot Group in Nepal, Shumar Formation in Bhutan and Buxa Group in Darjeeling-Sikkim. The *Fourth Cycle* is separated from the Third Cycle by a major diamictite, formerly known as Blaini Boulder Bed, in Himachal Pradesh and Uttarakhand. The Fourth Cycle occurs in two parallel belts called the Outer Krol Belt over the Simla Group and Inner Krol Belt above the Jaunsar Group. The Terminal Precambrian to Eocambrian Tal Group occurs in the Inner Krol Belt. The generalized stratigraphy of Krol Group towards the top consists of black slate, slaty quartzite and dolomitic limestone (Infra Krol), overlain by Krol Group *sensu stricto* consisting of quartz arenite with phosphatic shale; shale, dolomite, oolitic limestone and gypsum lenses; arenite, dolomite, limestone, phosphatic chert, black shale and local conglomerate. Krol Group contains fossil algae, acritarchs, stromatolites and oncolites. The most distinctive biota is Ediacaran fauna that represents an assemblage of soft-bodied metazoans (mostly coelenterates), metaphytic algae and trace fossils. The Ediacaran fauna equates the Krol Group with Terminal Proterozoic. The top shale of Krol Group gives Rb-Sr whole rock isochron age of 626±13 Ma. The overlying Tal Group comprising shale, sandstone, limestone, chert and phosphate, encloses abundant microshelly fauna of lower Cambrian age. The equivalent rocks of the Fourth Cycle in Nepal and Arunachal Pradesh are parts of Nawakot and Bomdila Groups respectively.

## Proterozoic ('Purana') Sedimentary Basins

*Proterozoic ('Purana') Sedimentary Basins* are flat lying, unmetamorphosed and peripherally deformed cratonic basins. They cover an area of about 150000 km$^2$, and occupy nearly 20% of the Indian shield. They contain several cycles of QCP suite ranging in thickness from 100 to 10000 m and deposited intermittently with frequent hiatuses over a time span of 800 m.y. from 1800 Ma to 1000 Ma. They expose thick unconformity-bounded transgressive and regressive sequences deposited in shallow water at 15-20 m depth. The common depositional environments are fluvial to shallow marine, grading into shelf-slope-basin settings. Aeolian and evaporitic successions are rare, and glacial environments are not established. These depositories are called 'Purana' basins in Indian stratigraphy like the Riphean and Vendian of Russia. The sub-horizontal sequences in these basins are deposited on the crystalline basement with a profound unconformity, earlier called Eparchaean unconformity, a term that has lost relevance in modern stratigraphy. These basins are epicratonic, pericratonic and inter-cratonic. The surrounding gneissic and granitic terrains have acted as a source for the sediments of these basins. The basins are a rich source of limestones and dolomites, besides barite and phosphorite. Kimberlites within and surrounding the basins are a good source of diamonds.

The *Palaeoproterozoic (1600-1800 Ma) basins* are small in extent and have basic volcanics in basal sections. They are linked spatially to contemporary pericratonic fold belts, e.g., Bijawar, Gwalior and Sonrai basins and Harda Inlier with Mahakoshal-Hindoli belts, Abujhmar basin with Kotri-Dongargarh belt and Papaghni sub-basin of Cuddapah basin with Nellore-Khammam schist belt. *Bijawar basin* consists of basal conglomerate, thick pile of basalt, stromatolitic dolomite, basic sill, sandstone, ferruginous breccia, shale and phosphorite. Rb-Sr age of lava and sill is 1700-1800 Ma. *Sonrai basin* consists of basal 'grit' and pebble beds overlain by a variety of shales signifying different environments of deposition. Basic flows, chert, phosphorite and dolomite are intercalated with shales. *Gwalior basin* contains basal conglomerate and 'grit', glauconitic sandstone and stromatolitic limestone, overlain by shale, jasper and sandstone interspersed with tholeiitic basalts and sills. Rb-Sr age of basic lava, sill and dyke is 1700-1800 Ma. *Harda Inlier* in Narmada valley consists of quartzite, chert-breccia, limestone, stromatolitic dolomite, sandstone, shale and contemporaneous lava flows. The dolomite contains lead-zinc occurrences. *Abujhmar basin* commences with basal conglomerate and arenite, shale and tholeiitic basalt. It has faulted boundaries in the east and west.

The *Mesoproterozoic (1600-1000 Ma) basins* are large, having no mafic volcanics. Some of the prominent basins such as the Cuddapah, Pranhita-Godavari, Bastar, Khariar and Chhattisgarh are peripherally deformed and feebly metamorphosed along the marginal zone of the Eastern Ghats mobile belt. The major sedimentary basins are: (i) the great Vindhyan basin encircling the Bundelkhand craton, (ii) Chhattisgarh, Khariar and Bastar basins (Indravati, Sabari and Ampani) on Bastar craton, (iii) Pranhita-Godavari basin between

Dharwar and Bastar cratons, and (iv) Cuddapah, Kaladgi and Bhima basins on Dharwar craton.

### *Vindhyan Basin*

The largest single 'Purana' basin is the sickle-shaped NE trending *Vindhyan basin.* It wraps around Bundelkhand granite and has faulted contacts with the adjacent cratons. The major structure of the basin is a synclinorium with axis curving along the centre of the sickle-shape. Lithostratigraphy of the basin in the ascending order is Semri, Kaimur, Rewa and Bhander Groups. Semri Group consists mainly of basal conglomerate, glauconitic sandstone and stromatolitic carbonate, followed by felsic volcanics and tuffs (porcellanite), shale, limestone and sandstone. Kaimur Group is essentially a sandstone-shale association. The shale is pyritiferous and carbonaceous. Rewa Group has frequent lateral facies changes. The basal shale and sandstone are overlain by diamond bearing conglomerate at Panna, followed by shale and immature sandstone. Bhander Group is conspicuous for lateral pinching and swelling. The basal shale contains a thin diamondiferous conglomerate near Panna. The shale has halite casts and the succeeding limestone contains algal mats and stromatolites. The overlying pink to purple sheet sandstone has intercalations of shale with halite casts and stromatolitic limestone. The pink sandstone is a valuable building stone. The total sediment thickness of the basin is about 5000 to 6000 m. The basal fluvial to transgressive regime of continental shelf is followed by lagoonal and tidal flat settings. The deposition ceased under tidal and partial aeolian regimes. Local arid and evaporitic environments are also noticeable. Palaeocurrent studies indicate palaeoslope towards northwest, suggesting that the Vindhyan shallow epeiric sea was connected to the main sea in the northwest. Silicified tuffs and porcellanites yield SHRIMP U-Pb zircon ages of ~1600 Ma for Semri Group. The kimberlites of Panna intruding Kaimur Group have given Rb-Sr ages of 1100-1150 Ma. Bhander Group may be late Mesoproterozoic. Megafossils of *Tawuia* and *Chuaria* along with cyanobacteria, acritarchs and fungal remains are reported from the basin. Stromatolites are widespread. Small Shelly Fossils (SSFs) recorded from Semri Group have been disproved, but Ediacara Fauna from Bhander Group are recently reported. The biota of Vindhyan basin are not time markers, but suggest a broad Neoproterozoic age for the upper units.

### *Chhattisgarh Basin*

*Chhattisgarh* basin (1600-1000 Ma) is the largest 'Purana' basin of Bastar craton and is linked to the other basins of Khariar, Ampani, Indravati and Sabari through many outliers. It is delimited by Kotri-Dongargarh belt in the west, Satpura mobile belt and Mahanadi graben in the north, and Eastern Ghats mobile belt in the east. In the south, it unconformably overlies gneissic basement that includes Kanker-Mainpur and Sambalpur granites, and Sonakhan 'greenstone belt'. It is a roughly rectangular basin covering an area of 36000 sq. km. The basin contains 2500 m thick sediments with minor felsic volcanics and pyroclastic rocks. Vast limestone and dolomite resources of the basin feed the Bhilai Steel Plant and many cement factories nearby. The lithostratigraphy of the basin comprises the Singhora, Chandrapur and Raipur Groups. The basal Singhora Group consists of a fining upward sequence of conglomerate-quartzite-shale-felsic volcanics representing a fluvial fan deposit. After a hiatus, conglomerate-arkosic sandstone beds are followed by a shale-dominated sequence of Chandrapur Group. The conformably overlying Raipur Group consists of three carbonate-shale cycles, intercalated with chert, phosphatic limestone, turbiditic shale, gypseous shale, welded tuff, acid tuff and porcellanite. Basic dykes intrude at different levels but their age (Proterozoic or Gondwana) is uncertain. The overall depositional environment varies from prodelta, lagoon, tidal flat, shoreface and deep shelf, with local coastal *sabkha*. The disposition of facies belts and palaeocurrent directions indicate NNW palaeoslope with open marine circulation along a seaway in the north at the present site of Son-Narmada trough.

### *Khariar Basin*

The *Khariar (Noagarh) basin* to the south of Chhattisgarh basin consists of two sequences of lower sandstone-limestone and upper sandstone-shale separated by a disconformity. The succession is called the Pairi Group. The overall depositional setting is shallow marine with local euxenic and arid conditions. Kimberlites of the Mainpur kimberlite field occur near the basin. Sedimentary dykes in the basement granite suggest the link between Chhattisgarh and Khariar basins. The small Ampani basin and Keskal-Singenpur outliers connect Chhattisgarh-Khariar to the Indravati basin of Bastar region. These outliers preserve the basal arenaceous successions of the 'Purana' basins.

### *Indravati and Sabari Basins (Bastar Basins)*

The *Indravati basin* consists of 350-550 m thick sequence of sandstone-shale-limestone-dolomite-shale. Indravati Group overlies basement granites and gneisses on all sides, and the Kondagaon granulite belt in the north. Basal arkose occurs as thin beds and as sedimentary dykes (Neptune dykes) filling the joints in basement granite, that are different from clastic dykes which 'intrude' consolidated sediments. The sedimentary dykes are seen far from the present basin boundaries, suggesting the past extent of the basin prior to erosion. The basal conglomerate contains clasts of granite and Sukma metasediments. Kanger Limestone is of cement grade. The basin has a major offset along the E-W trending Sirsiguda fault. Important kimberlite bodies like Tokapal, Bhejipadar and other minor ones in the vicinity intrude the Jagdalpur shale occurring at the top of the sequence. *Sabari basin* is connected to Indravati basin through Chedrapal outlier. The basin has similar lithology, but has lesser extent. At the contact with the marginal zone of Eastern Ghats mobile belt, the Sukma shales are deformed into low-grade phyllites.

### *Pranhita-Godavari (P-G) Basin*

The P-G basin occurs in two parallel NW-SE trending basins viz., the western Pakhal (or Mallampalli) basin on Dharwar craton and eastern Albaka basin on Bastar craton, with the intervening Gondwana basin of the Godavari graben. The basins are probably part of a single large basin that formed after amalgamation of Dharwar and Bastar cratons during Palaeoproterozoic (~1800 Ma). The basin is 400 km long and 100 km wide, including the 40 km width of Gondwana basin in the middle. The aggregate thickness of sediments is about 6000 m. The P-G basin has two prominent outliers (Sharnavala and Kadam) and three inliers (Mailaram, Chinnur and Chandrapur). The succession is called the composite Godavari Supergroup by some authors, and as independent and homotaxial Pakhal and Albaka Supergroups by other authors. The Pakhal Supergroup is divided into Mallampalli, Mulug and Penganga Groups separated by disconformity or fault, and the younger Sullavai Group separated by angular unconformity. Mallampalli Group has basal arkose and conglomerate resting unconformably on Karimnagar granulite belt with its enclave suites. It is followed by a sequence of quartzite (locally glauconitic), stromatolitic dolomite and shale. Mulug Group consists of repetitive beds of shale, chert, dolomite and sandstone overlying basal arkose. Mallampalli and Mulug Groups are formed in a lagoonal to tidal flat environment. The overlying Penganga Group comprises sandstone, limestone, manganoan chert and shale, starting with a shelf, changing into carbonate platform and ending in deepwater mud that suggests an epicratonic sea joining the open sea. Sullavai Group consists of overlapping arenaceous units with basal conglomerate and banded to spotted red sandstone. The sheet sandstones are deposits of streams and aeolian sand seas. Albaka Supergroup consists of Somanpalli Group (equivalent of Mallampalli Group), Mulug Group, Albaka or Pamanuru Sandstone (equivalent of Penganga Group), and Usur Group (equivalent to Sullavai

Group). The overall environment is near shore to offshore, tidal flat and alluvial fan at the top. Sedimentological studies indicate that there was a southerly sloping embayment acting as a pathway for marine transgression from the east. The P-G basin is marked by NW trending tight folds and thrusts with top-to-NW and top-to SW movement. The structures in the southeast margin are deflected to become parallel to the trends of EGMB. There is corresponding increase in metamorphism from NW to SE, from slates and phyllites to mica schists containing chloritoid, andalusite, garnet, staurolite and kyanite. There is a veiw that high-grade pelitic schists may belong to Khammam schist belt. The deformation and metamorphism are probably related to Eastern Ghats orogeny.

### *Cuddapah Basin*

Cuddapah basin is a crescent shaped, easterly concave, N-S trending basin in Dharwar craton, covering an area of 44000 km$^2$. It is the second largest basin after the great Vindhyan basin. The western arcuate boundary marks the profound angular unconformity with the basement gneisses enclosing greenstone belts of EDC, as well as non-conformity with the Archaean basement granite. The greenstone belts overlain by the basin in the south are Kadiri, Veligallu and Tsundupalle, and they re-emerge from underneath the basin in the north along their arcuate strike extensions as the corresponding belts of Jonnagiri, Raichur-Gadwal and Peddavuru. The concave eastern margin of the basin is marked by a thrust that is parallel to the Nellore schist belt, EGMB and the East Coast. A major mafic dyke swarm underlies the basin from Chittoor in the south to Mahboobnagar in the north. The western half of the basin is undeformed and consists of four sub-basins of Papaghni, Kurnool, Srisailam and Palnad. The sub-basins are geographically interlinked, but were sites of deposition at different times, suggesting their diachronous evolution. The eastern half of the basin is deformed into a variety of folds forming a fold-thrust belt called the Nallamalai fold belt. The cratonic sub-basins and the Nallamalai fold belt are separated by a prominent boundary called the Rudravaram Line. Papaghni sub-basin, with its significant basic volcanics and sills of ~1800 Ma age, is comparable to the other Palaeoproterozoic basins like Bijawar, although it occurs as a sub-basin within the Cuddapah basin.

The lithostratigraphy of Cuddapah basin comprises Papaghni, Chitravati and Nallamalai Groups, and Srisailam Quartzite, separated by unconformities and are included under Cuddapah Supergroup. A younger sequence called Kurnool Group unconformably overlies the Cuddapah Supergroup in the Kurnool and Palnad sub-basins. Numerous quartzite horizons in the various sub-basins pose serious problems of correlation, leading to multiple points of view, but the broad consensus of the geological team of GSI that mapped the terrain has been favoured here. Papaghni Group consists of basal quartz pebble conglomerate-quartzite (Gulcheru Quartzite) overlain by shale, siltstone, sandstone, and stromatolitic, phosphatic, uraniferous and oolitic dolomite (Vempalle Dolomite). Intercalated with this sequence are amygdular tholeiitic basalt and basaltic andesite (Kuppalapalle Volcanics) and sills of picrite, dolerite and gabbro. These mafic rocks follow the arcuate pattern of Papaghni sub-basin. The overlying Chitravati Group consists of basal conglomerate, quartzite and thick shale interbedded with dolomite, cherty tuffs, crystal tuffs, ash flows and ignimbrites. Pillowed spilitic lava is rarely seen. A major quartzite horizon (Gandikota Quartzite) is seen at the top of this sequence. The succeeding Nallamalai Group comprises a deformed and feebly metamorphosed shale-felsic tuff-siltstone-quartzite-dolomite sequence in the Nallamalai fold belt. A unique occurrence of a large bedded barite deposit at Mangampeta occurs within shale-tuff unit (Pullampet Formation), and consists of barite rosettes and celsian (barium felspar). Pb-Zn mineralisation is noticed in the dolomite of Cumbum Formation at Agnigundala and Zangamrajupalle-Varikunta. Srisailam Quartzite at the top of Cuddapah Supergroup is a glauconitic and ferruginous sandstone associated with minor shale within the Srisailam sub-basin. There is a wide range of shallow marine environments for the Cuddapah sequence, starting from fan delta, tidal flat, lagoon and shallow shelf to offshore. After prolonged quiescence following the completion of the Cuddapah cycle, Kurnool Group comprising two main sedimentary cycles of quartzite, limestone and shale was deposited in the Kurnool sub-basin. The basal Banganapalle conglomerate contains placer diamonds probably derived from kimberlite diatremes found in the surrounding granitic basement. Numerous kimberlite and lamproite bodies have been recently located in the surrounding Wajrakarur and Narayanpet fields. Narji Limestone is of cement grade and the flagstones in the succession are used as roofing stones and paving stones called popularly as 'Cuddapah slabs'. Structurally, the Nallamalai fold belt consists of isoclinal to tight and open folds in three phases. Along the major thrust at the eastern margin, the older Nellore schist belt and gneissic basement override the Cuddapah slates, phyllites and quartzites of Nallamalai fold belt, leaving klippen in the east as at Udayagiri. The thrusting is probably multi-episodic affecting the Cuddapah and Kurnool sequences. The initiation of the basin may be due to asthenospheric doming causing the emplacement of mafic dyke swarm. The basic volcanics and sills of Papaghni sub-basin, with their gravity and magnetic highs may suggest the presence of a major basic body (layered intrusion) or a magma chamber at depth. Sedimentation in the basin followed the pattern of other 'Purana' basins. The tectonic movements associated with EGMB have generated the Nallamalai fold-thrust belt. The age of the basin is bracketed between 1500 and 1800 Ma, as evidenced by the Rb-Sr ages of Vempalle and Tadpatri basalts and basic sills at ~1800 Ma, age of U-mineralisation in Vempalle dolomite at 1800 Ma, age of intrusive granites in the eastern part of the basin (1500-1600 Ma) and of Mangampeta felsic tuff (~1500 Ma). The age of Kurnool basin is late Mesoproterozoic (~1000 Ma) as seen in the age of diamondiferous kimberlite at 1000-1100 Ma and intrusive dolerite at 980 Ma. The microfossils and trace fossils of Kurnool Group broadly confirm this age.

### *Kaladgi Basin*

Kaladgi basin is an E-W trending irregular basin having 8300 km$^2$ area, and is underlain by gneisses, granites (including Closepet Granite) of Dharwar craton in the south and east, and overlain by Deccan Trap in the north. Inliers of granites and parts of schist belts are seen within the basin. The basin consists of the main Kaladgi basin and the younger Badami sub-basin. It is an intracratonic basin deformed in the centre, and is not related to mobile belts. It consists of two cycles of conglomerate, quartzite, chert breccia, dolomite, limestone and shale. Oolitic chert and banded hematite jasper form marker horizons in the upper cycle. The depositional setting changes from transgressive coast through tidal flat and shelf to offshore and carbonate platform. Palaeocurrent directions indicate northerly palaeoflow. Kaladgi sediments are folded into tight to isoclinal doubly plunging folds in the middle of the basin. The rocks have also undergone low-grade metamorphism. Pegmatites and dolerite dykes intrude the basin. Vast resources of cement grade limestones are present in the basin. Isotopic dating of dolomite indicates an age of 1600-1700 Ma. The unconformably overlying Badami Group in Badami sub-basin is nearly undeformed and flat bedded, comprising basal conglomerate and purple sandstone housing the famous Badami cave temples, and brown laminated shale with siltstone and limestone interbeds. Badami sequence reflects coastal to shallow shelf setting and indicates southwesterly palaeoflow. Trace fossils in Badami Group indicate Vendian age but this needs confirmation by further work.

### *Bhima Basin*

Bhima basin is a NE trending sinuous basin that unconformably overlies the granites of EDC in the south and underlies Deccan Trap in the north. It has vast resources of limestone and the newly discovered uranium deposit at Gogi. The stratigraphy consists of basal conglomerate-sandstone, flaggy limestone and chert at the bottom, and arenite, shale with barite, limestone and shale in the top. Bhima sediments are practically horizontal, but disturbed locally by faults. The favoured environment is transgressive coast, tidal flat and carbonate platform. Microbiota and palynofossils indicate Neoproterozoic age for Bhima Group.

## Supercontinental Cycles

The assembly and dispersal of continents forming a supercontinental cycle provide a conceptual framework for the evolution of continental crust through geological time. Since these assemblies and dispersals occur frequently, there are several supercontinental models with different definitions and different names. Nevertheless, configuring of supercontinental networks helps in integrating global geology better, and that may spawn new models of the evolutionary history of the Earth.

There are about 35 Archaean cratons in the Earth, some of which have assembled and dispersed as supercratons (Bleeker, 2003). It has been speculated that these supercratons were Vaalbara (3.5 Ga), Superia (2.7 Ga) and Sclavia (2.5 Ga). It is not certain whether these supercratons were independent entities or were part of the sprawling supercontinent of Kenorland. Similarities between the Slave, Dharwar, Wyoming and Zimbabwe cratons suggest that they may have formed part of Sclavia.

Supercontinental cycles are recognized with greater certainty in Proterozoic. Nuna appears to be the first true supercontinent formed around 1.9 Ga. Mesoproterozoic mobile belts (1.5-1.6 Ga) surrounding cratons have sutured the crustal fragments on a global scale to produce the Rodinian supercontinent. In the Indian shield, the Satpura mobile belt sutured the Bundelkhand (Vindhyanchal) and Deccan protocontinent during this period, and formed part of Rodinia. The Archaean cratons of Dharwar, Bastar and Singhbhum were amalgamated sometime in Palaeoproterozoic (~1800 Ma), rather than in Archaean as believed earlier, and their joins (or sutures of some authors) are now concealed under Gondwana graben (Godavari and Mahanadi). These cratons may have formed part of the global Nuna, Ur or Columbia supercontinent. After their amalgamation, epicontinental seas ('Purana sea') evolved concurrently with the evolution of continental margin orogenic belts (e.g. Eastern Ghats mobile belt). The EGMB developed in Grenville times (1.0-1.1 Ga) to form East Gondwana. The development of younger 'Purana basins' (Kurnool, Badami, Sullavai, Bhander) coincided with the evolution of Pandyan mobile belt in Pan-African times that finally resulted in the suturing of East and West Gondwana (Terminal Proterozoic, ~550 Ma) to form the 'Pannotian' supercontinent. The dispersal of the supercontinent led to northerly migration of India until the Himalayan collision (Fig.2.6a,b).

Comparison of the geology of parts of south India with those of

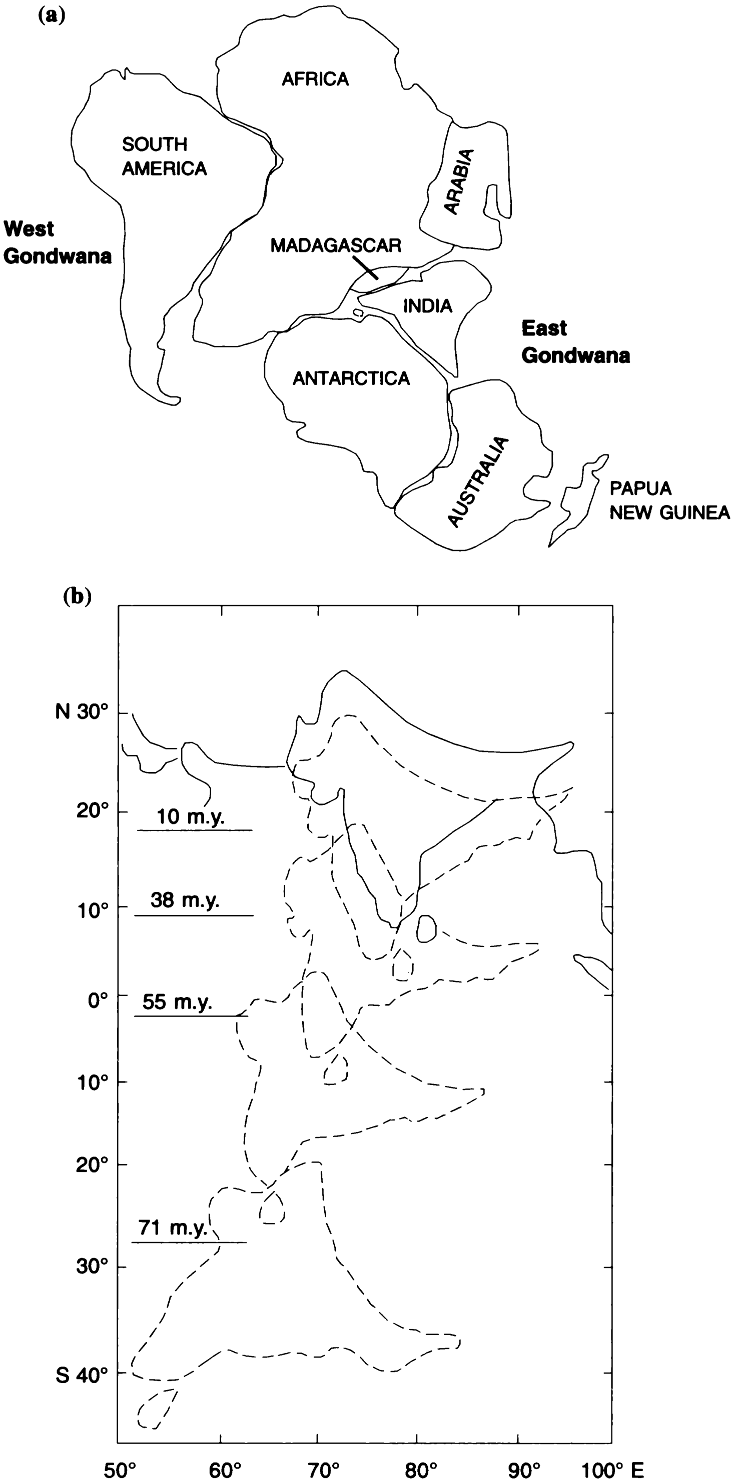

(a)
AFRICA
SOUTH AMERICA
ARABIA
West Gondwana
MADAGASCAR
INDIA
East Gondwana
ANTARCTICA
AUSTRALIA
PAPUA NEW GUINEA
(b)
N 30°
20°
10°
0°
10°
20°
30°
S 40°
10 m.y.
38 m.y.
55 m.y.
71 m.y.
50°
60°
70°
80°
90°
100° E

**Fig.2.6.** (**a**) India as part of Gondwanaland. (**b**) Flight of India from Antarctica to Asia.

Madagascar shows that the western part of Dharwar craton seems to have its counterpart in the northeastern part of Madagascar. This is established based on similarity in lithology and structure besides radiometric ages. Sri Lanka is made up of four domains of (i) Highland Complex, (ii) Kadugannawa Complex, (iii) Wanni Complex, and (iv) Vijayan Complex. The Trivandrum and Madurai Blocks in the Southern Granulite Terrain of India have lithological and petrological characteristics similar to those of the Highland Complex. Since the oldest marine formations on the southeastern coast of India and the northwestern coast of Sri Lanka belong to the Cretaceous, it is surmised that Sri Lanka should have separated from India during late Jurassic or a little later. It is likely that a continental block might have submerged in the ocean forming the present Palk Strait between India and Sri Lanka.

In the Indian Ocean, the Madagascar Basin is located between southwest Indian Ocean Ridge, Madagascar Ridge, Mascarene Basin and Central Indian Ridge. This basin has been created by the spreading of Central Indian Ocean. The Mascarene Basin lies between Madagascar and Mascarene Plateau and appears to be the northwest extension of the Madagascar Basin. A Cretaceous age is indicated for this basin. Separation between Madagascar and Seychelles is estimated to have taken place about 90 Ma ago. India and Seychelles were, however, separated around 60 Ma ago. This separation was caused by the then active Carlsberg Ridge. The latest to part company with the mainland is the Laccadive Ridge resulting in the present configuration of the west coast of Kerala (Fig.1.11).

## Phanerozoic

Within a period of 550 Ma from Cambrian to Holocene, Indian plate was subjected to many geological processes. Some of the major ones were the following: (i) deposition of Gondwana sediments in faulted troughs, (ii) opening of Indian Ocean, (iii) eruption of Deccan and Rajmahal continental flood basalts, (iv) closure of Tethys and uplift of Himalaya as a result of continental collision, (v) deposition of sediments in the Indo-Gangetic plains, (vi) onset of monsoon system, and (vi) a few periods of glaciation. Within this vast period, different forms of life developed, and some faced extinction both among the fauna and the flora. During the Phanerozoic, both fresh water non-orogenic and marine orogenic deposits were formed. The fresh water deposits are the Gondwana sediments and the marine deposits are mainly in the Himalaya.

### *Palaeozoic*

During the Palaeozoic era (about 300 m.y.), India was a part of Gondwana, along with other southern continents (Fig.2.6a). In the beginning the entire Gondwana drifted as a plate for sometime. This is inferred from the wandering of the South Pole, recognized from palaeomagnetic studies. Subsequently there was break up of this huge plate and peninsular Indian part slowly moved northeast and north after a slight anticlockwise rotation (Fig. 2.6b). As it moved, some minor parts of it along the margin broke away to form independent lands like Madagascar, Seychelles and Sri Lanka. The Himalayan basin existed as a marine basin for most part of the Palaeozoic era. The Tethyan Himalaya contains some of the classic exposures of Palaeozoic strata (Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian) in Kashmir, Zanskar-Spiti and Kumaun basins in northwestern Himalaya. However, the Lesser Himalayan region does not contain a continuous succession of the entire Palaeozoic strata. Ediacaran fauna (soft-bodied metazoan creatures of uncertain phylogenic affinity) have been reported since over three decades from this part of Himalaya, bridging the gap as it were between the uppermost Neoproterozoic and the Cambrian, particularly in northwestern Himalaya. Among the strata of the Palaeozoic, only those of Cambrian, Carboniferous and Permian have strong representation here, though strata of the intervening times are not altogether unrepresented. Because of intense deformation and mostly containing only a few fossiliferous horizons, their contribution to the Palaeozoic history of this region is limited. However, during the Early Cambrian the sea stretched almost from Salt Range in Pakistan through Pir Panjal in Kashmir, Chamba-Tandi belt in Himachal, through Garhwal in Uttarakhand to even eastern Arunachal, though with breaks in their strike continuity. In the Lesser Himalayan tectogen at the close of the Early Cambrian, about 525 Ma ago, later than Vendian age (680 – 545 Ma), sedimentation almost came to an end. This might have been partly due to a diastrophism called Pan-African (~500 Ma), which affected parts of Jammu and Kashmir and Himachal Himalaya.

In the Palaeozoic history of the Indian subcontinent, a noteworthy feature is the recognition of the transition from Precambrian to Cambrian in terms of records of primitive life. In the Himachal Himalaya, Krol D Limestone of the Krol Group underlying Tal Group of Early Cambrian age is reported to contain Ediacaran fauna, which is a distinctive assemblage of soft-bodied metazoans (mostly coelenterates – medusoid frondoid forms), metaphytic algae and trace fossils. Similarly in the Blaini-Krol succession in Uttarakhand, a detailed study of the various fauna clearly indicates the transition from Neoproterozoic to Early Cambrian. Acritarchs, small shelly fossils (ssf) and stromatolites have been reported. During Early Permian there was a transgression of the sea through Salt Range in Pakistan and along Rajasthan and Narmada valley. Permian glaciation, which deposited Talchir Boulder Bed in the Gondwana basins, laid down glacial and cool water sediments in Lesser Himalaya with characteristic cool water fauna. Permian witnessed prolonged volcanic activity in sections of Himalayan belt marking conspicuous changes in the life of the succeeding Mesozoic era. These formed islands in the Tethys Sea. In the peninsular part of India, Palaeozoic is represented only in Badhaura in Rajasthan, and Umaria and Manendragarh in Madhya Pradesh as marine incursions.

Though the classification by Middlemiss of upper Palaeozoic into Muth Quarzite, Syringothyris Limestone, Fenestella Shale and Agglomeratic Slate is still followed by some, because the nomenclature is not in conformity with the Code of Stratigraphic Nomenclature, these are now referred to as Muth, Wazura, Aishmuqam, Ganeshpur and Pindobal Formations.

Almost all major invertebrate phyla are represented in the Palaeozoic. Trilobites, brachiopods, cephalopods and foraminifera occurred in force during certain periods facilitating correlation. One of the conspicuous features during the Palaeozoic is the occurrence of Fenestella–bearing shale marker horizon throughout Tethys Himalaya. Amphibians evolved from fish of Silurian. A few representatives of charophyta and algae formed the plant kingdom in the earlier periods, but from Carboniferous onwards, luxuriant vegetation came into being.

### *Gondwana Supergroup*

A major part of the supercontinent Gondwana has a well-preserved record of Archaean to Proterozoic events. But its subsequent history, particularly from Lower Permian to Upper Jurassic, spanning a period of about 100 m.y., is of particular interest to geologists in the southern continents. Peninsular India primarily and a few pockets in Lesser Himalaya contain records of essentially terrestrial sediments with plant fossils referable to the now well known Gondwana Supergroup. What is interesting to be noted here is that the concept of Gondwana and Continental Drift were vehemently opposed even when put forward with some tangible evidences on lithology and biota (flora and vertebrate fossils), because the actual mechanism of movement of large chunks of landmass could not be explained. However, the concepts of ocean-floor spreading, plate tectonics, mass extinction, mantle plumes, hotspots etc. have now firmly supported the earlier hypothesis of Continental Drift. Major characteristics of the Gondwana Supergroup include a basal glacial bed, presence of large coal seams, common fossils – mainly plants and vertebrates, and end-phase volcanic eruptions, not necessarily contemporaneous in all the regions where they occur. Though different types of Gondwana assembly are put forward to explain the comparable characteristics of this supergroup in the different southern continents, the one contributed by Veevers and Tiwari (1995) seems to present a comprehensive review of the structure and sedimentological evolution of this great master basin. According to this, the Indian subcontinent is juxtaposed between Antarctica on one side and Africa-Madagascar on the other. Based on this, they propose that the Gondwana master basin was a part of a 7500 km wide alluvial fan source from upland in East Antarctica and it was disrupted during stages of rifting and sea-floor spreading. Though called as rift basins, it is now realized that these did not start as rifts, but ended as half and full grabens due to syn-, to late depositional episodic faulting. In certain cases tectonic elements of the Precambrian might have provided the basic framework. Whereas we owe the preservation of coal seams in different basins to faulting on either side or both sides, it is equally possible some seams might have been lost due to subaerial erosion from those parts now seen as horsts within the basin. To some extent the lithology reflects regional changes in climate, which perhaps may be due to the Indian plate having passed through different climatic belts during its northward migration. In the case of vegetation also this is reflected, though certain species have survived in spite of such changes. Vertebrates, particularly those belonging to sauropods, became prominent only during the later part, some continuing on to the end of Mesozoic.

A vast thickness of sediments deposited mostly along the three major rift basins of Damodar, Mahanadi and Pranhita-Godavari belongs to Gondwana Supergroup. There are a few deposits along the east coast of India as well, which contain plant fossils similar to those found in the rift basins. The most commonly occurring fossils are those of *Glossopteris, Gangamopteris, Schizoneura* and *Noeggerathiopis* in the Lower Gondwana and *Ptilophyllum, Pterophyllum* and *Dictyozamites* in the Upper Gondwana. Palynofossils are now found to be of considerable importance in correlation among the Gondwana strata. These also throw light on climatic variations during deposition of the associated sediments.

The sequence in Damodar valley has been taken as the type area for Lower Gondwana to correlate with sediments in other basins in the country. The sequence is Talchir, Karharbari, Barakar, Barren Measures, Raniganj and Panchet. But in the case of Upper Gondwana, local names are given in some cases for example, Denwa, Bagra, Chaugan and Jabalpur in Narmada valley, but Yerrapalli, Bhimaram, Maleri, Dharmaram, Kota, Gangapur and Chikiala in Pranhita-Godavari valley. There is no distinct unconformity in most of the places where designated Lower and Upper Gondwana sediments occur. It is this ambiguity that has led to both two-fold and three-fold classifications of Gondwana Supergroup in India.

Correlation even at stage level is usually possible in marine strata where they abound in invertebrate fossils, with some species of short range in time.

This can be seen among the marine strata of Triassic of Spiti, Jurassic of Kutch and Cretaceous of Trichinopoly (Tiruchirapalli or Tiruchi). This has not been possible in the case of Gondwana strata because of the longer range of plant fossils in time and fewer unconformities within the sediment piles. Occurrence of marine fossils of definite age within the lowermost strata in Madhya Pradesh and uppermost strata in Kutch has helped in arriving at the total range in time of the Gondwana Supergroup in India. Tripartite and two-fold classifications are in vogue depending upon the criteria being employed – unconformities, climate and plant fossils.

### *Mesozoic*

A slow transgression in parts of the Himalayan terrain commencing at the end of the Permian and continuing up to a major transgression along the east coast of India in the middle Cretaceous left behind strata of Mesozoic (Triassic, Jurassic and Cretaceous) in both the Himalayan terrain and parts of peninsular India. Mesozoic is represented by sediments, volcanics and ophiolites in the Indus Tectonic Zone of Ladakh, also referred to as the Indus Suture Zone. Though this eon had a span of only about 185 m.y., much less than that of the Palaeozoic (290 m.y.) but in terms of thickness of sediments, facies changes and variety of life, this has much to offer for study. The invertebrate fauna in the seas were comparable to many in other parts of the world. Intercontinental correlation could also be established. During Mesozoic, Neotethys got ushered in Lower Triassic. Marion hotspot in Bay of Bengal resulting in its opening up is dated at 160 Ma. Rajmahal volcanism also commenced around 115 Ma in Jharkhand. Sylhet Traps in Meghalaya poured over a period of 20 m.y. in Early to Middle Cretaceous. These two are considered to have been the result of Kerguelen hot spot track in the Indian Ocean. Madagascar got separated from India around 90 Ma in Turonian, when a major drop in sea level also of about 125 m is estimated to have taken place. Much later, during Maastrichtian, a drop of 75 m in sea level is suggested.

A sequence of strata in the Guryal ravine section in Kashmir has been put forward as the type section containing the Permian-Triassic boundary. The contention is that it contains *Productus* (brachiopod) of Permian age in association with Lower Triassic bivalve *Claria.* Conodontists favour the boundary to be placed above *Otoceras woorwardi* zone, while ammonitologists seem to stick to the base of the *O. woodwardi* zone. The International Stratigraphic Commission is yet to approve this as Global Boundary Stratotype Point (GBSP).

Most of the explored *Triassic* is from Jammu and Kashmir, Himachal Pradesh (Spiti), Uttarakhand (Painkhanda, Malla Johar), Nepal and Sikkim.

Triassic strata are, however, reported from subsurface in Rajasthan and Kutch. The thickness of the formations in the Himalayan terrain shows profound variations among the same correlatable stratigraphic units indicating the influence of transgressions and regressions within the long basin extending NW-SE. For example, in the Tethyan Himalaya, Triassic is about 4000 m in Kashmir, but 1000 m in Spiti (Himachal Pradesh) and only 400 m in Kumaun (Uttarakhand). Most of the stages and substages of Triassic have been identified in the Triassic Lilang section (Himachal Pradesh) and are comparable with those in adjoining countries. The 'Exotic Blocks' of Malla Johar (Kumaun) contain Triassic fossils besides those of Permian and Jurassic. The Triassic in Kashmir is represented by Tindra, Khreuh and Wuyan Formations. In Himachal Pradesh in Spiti, it is the Lilang Group with Mikin, Kaga, Choumule, Sanglung, Hangrang, Alror, Nunluka and Kioto that represent Triassic, whereas in Uttarakhand it is the Shal Shal Formation with Rambakot, Niti, Hoti, Rimkin and Kioto as Members in Painkhanda, but the Lilang Group is made up of Chocolate Limestone, Niti Limestone, Kalapani Limestone and Kuti Shale in some of the valleys. It may be noted that in a few of the sections rocks equivalent to Rhaetian, uppermost Triassic, is missing.

Marine *Jurassic* rocks also occur along the Tethyan belt from Ladakh-Zanskar-Kashmir through Spiti to Malla Johar. They are best known from Kutch, though are present along the East Indian coast also. The Jurassic of Kutch has been a hunting ground to ammonitologists from different parts of the world, as it presents varieties of ammonites and what is more, assists in correlation at the level of sub-stages because of very short duration of some of the species, in time. Studies of Jurassic in the neighbouring regions have enabled reconstructing palaeogeography of the times in considerable detail. In Kutch, Jurassic is partly represented by Patcham, Chari, Katrol and Umia extending from Callovian (late Middle Jurassic) to Tithonian and part of Umia extends beyond up to Aptian (late Lower Cretaceous). In Spiti it is represented by Kiogad/Spiti Formation, which extends from Callovian to Tithonian.

Marine *Cretaceous* is much better known for its extensive presence in Narmada valley, Trichinopoly in Tamil Nadu and in northeastern India, than in the Tethyan belt. In the Tethyan belt, for example, representatives of horizons from Berriasian (Lower Cretaceous) to Maastrichtian (Upper Cretaceous; Giumal and Chikkim Formations) are known, though not in any single section always. In peninsular India, however, they are present only from Valanginian to Albian in Kutch, from Aptian to Coniacian in Rajasthan, from Aptian to Maastrichtian in Trichinopoly (Uttathur, Trichinopoly and Ariyalur Groups), Cenomanian to Santonian in Narmada valley (Bagh Beds) and Campanian to Maastrichtian in Meghalaya (Sylhet Traps of Early and Middle Cretaceous and Mahadek Formation of Maastrichtian). Lameta Beds in Madhya Pradesh made up essentially of terrestrial deposits are considered to be of Maastrichtian age. Cretaceous period witnessed extensive volcanic activity in the Dras-Kargil zone of Kashmir. Slices of ophiolite blocks are tectonically emplaced within the sediments and lava flows here. Dinosaurs roamed around in parts of Gujarat, Madhya Pradesh and Andhra Pradesh during the late Cretaceous. The interesting part is the find of dinosaur eggshells in many places indirectly assisting in inferring environments of deposition of the associated beds.

### *Deccan Volcanic Province*

Deccan Volcanic Province (DVP) or Deccan Trap is one of the most remarkable continental flood basalt (CFB) provinces of the world, like those of Columbia River, Karoo, Parana and Siberia. DVP covers the Deccan Plateau, particularly the majestic hills of the Western Ghats or *Sahyadri*. Deccan Trap covers an area of 50,000 sq. km, together with double this extent concealed under the Arabian Sea. The composite thickness of flood basalts is about 3000 m. The volcanics are dominantly subaerial tholeiitic basalt flows, with subordinate picrites, picritic basalts and alkaline basalts. The alkaline basalts carry mantle nodules and cognate xenoliths locally. Volcano-plutonic complexes consisting of acidic to alkaline intrusives and flows, gabbros, dolerites, lamprophyres and carbonatites are emplaced within Deccan Trap in Saurashtra, Khambhat (Cambay), Rajasthan and Narmada valley. This igneous ensemble of volcanics, plutons and dykes in Deccan makes DVP a Large Igneous Province (LIP) of the world. Deccan volcanics have erupted close to the Cretaceous-Tertiary Boundary. They are closely related to mass extinction, global climate change and assembly of supercontinents.

One of the most important aspects of Deccan volcanism is the propagation of flood basalts for enormous distances. It was believed earlier that lavas erupted through closely spaced fissures. The presence of volcanic centers in DVP suggested an alternate mode of eruption. These modes of eruption may not be able to account for the flows travelling to long distances. Recent finds of a series of well-preserved lava channels and tubes show that they have acted as conduits for effective lava transport for long distances.

Deccan volcanics have erupted through the Precambrian crust of the Indian shield. They are underlain by Cretaceous sediments (Bagh, Lameta) called Infra-trappean. They are intercalated with sediments and ash beds (red bole, green earth) called Inter-trappean. The volcanics are nearly horizontal over vast areas except where tectonically disturbed. The lavas are thinnest in the east and they progressively thicken to two km in the west, probably due to pre-Deccan topography and faulting. The volcanics show younging from west to east. Lithostratigraphy and chemostratigraphy of Deccan Trap have been worked out in accordance with the stratigraphic codes into formations and subgroups under Deccan Basalt Group or Sahyadri Group.

DVP is broadly divided into four sub-provinces, viz, (1) Main Deccan Plateau occurring to the south of Narmada River, (2) Malwa Plateau to the north of Narmada River, (3) Mandla Lobe around Jabalpur, Seoni and Chhindwara, and (4) Saurashtra Plateau. A small outlier of Deccan Trap occurs near Rajahmundry on the East Coast. The Main Deccan Plateau, particularly the western region (called Western Deccan Province by some authors), is the best-studied sub-province. Lithostratigraphically, it is divided into seven formations of Salher, Ratangad, Indrayani, Karla, Diveghat, Purandhargad and Mahabaleswar. These formations are delineated on the basis of simple or compound flows, pahoehoe or aa flow types, and aphyric or felspar-phyric texture. Giant Plagioclase Basalts (GPBs) are good marker horizons to distinguish different formations. In the area around Mumbai, mafic and felsic flows, pyroclasts and gabbro to granite intrusions occur. This assemblage may form a younger unit called Borivali Formation or merely as Mumbai volcanic complex. It may be mentioned in general that older formations comprising compound pahoehoe flows are exposed in the north and west. Younger formations made of simple *aa* flows occur in the east and south, indicating an overall younging to the southeast. Recently, systematic geochemical mapping using similarities and differences in elemental abundances and ratios, and isotopic signatures have been used to devise a chemo-stratigraphic column for the western region of the Main Deccan Plateau, especially from well-exposed geological sections in the Western Ghats from Nashik to Mahabaleshwar and Pune to the West Coast. The chemo-stratigraphic column consists of three subgroups including twelve formations. The lower *Kalsubai Subgroup* comprises Jawhar, Igatpuri, Neral, Thakurvadi and Bhimashankar Formations. It consists of amygdaloidal compound flows separated by GPBs. Picrites (>18% MgO) and picrite basalts (>10% MgO) containing olivine and/or clinopyroxene phenocrysts are common in Kalsubai Subgroup. *Lonavala Subgroup* consists of Khandala and Bushe Formations. Khandala Formation is made of distinctive simple flows. Bushe Formation consists of a few distinctive, aphyric and amygdaloidal compound flows. Lonavala Group is characterized by high Ba/Ti and Ba/Sr values, and higher MgO for a given $TiO_2$ value. *Wai Subgroup* is made of five formations having simple flows with well-developed flow tops. They are Poladpur, Ambenali, Mahabaleswar, Panhala and Desur Formations. The boundary between Lonavala and Wai Subgroups is clear in the field and is marked by sharp elemental and isotopic change. The flows of Wai Subgroup are more highly evolved than the older flows. There is broad general correspondence between lithostratigraphy and chemostratigraphy. The only major difference is in Wai Subgroup, where two additional younger formations are identified on chemical grounds, but are not recognizable lithostratigraphically, and this may have to be reconciled by later work. The use of different GPB markers in the field has also led to the changes in the two classifications. The entire Deccan lava pile excluding the top formations of Mahabaleshwar, Panhala and Desur (Wai Subgroup) are reversely magnetized. Only the top formations are normally magnetized. This top-normal feature may be used as a significant marker in geological mapping. In the central, southern and southeastern part of the Main Deccan Plateau, the stratigraphic succession continues uninterruptedly from the one that is well established in the western part. The succession in Satpura Hills is affected by frequent faulting and thick alluvial cover and comparison with the Main Deccan Plateau is tenuous. In Mandla Lobe, most flows belong to Ambenali Formation, with some flows corresponding to Poladpur Formation. Detailed correlation is also not available for Malwa Plateau, Saurashtra and Kachchh (Kutch). Volcanics comparable to Ambenali and Mahabaleshwar Formations are found in the East Coast and are informally known as Rajahmundry Lavas.

*Alkaline lavas*: Pavagadh Hill near Vadodara (Baroda) exposes an ascending sequence of tholeiitic basalt, alkali olivine basalt, green tuff and rhyolites to alkaline flows. Coastal tracts and islands near Mumbai also expose a similar succession. In Narmada rift, alternations of tholeiitic and alkaline basalts are seen near Rajpipla. The alkali basalts of Kachchh and other areas contain mantle nodules of spinel lherzolite and cognate xenoliths of dunite, clinopyroxenite and pyroxene granulite. In St.Mary's Islands off Malpe near Udipi, columnar lavas of rhyolite, rhyodacite and granophyre are found.

*Volcano-Plutonic Complexes* associated with Deccan basalts occur in Saurashtra arch, and Narmada and Khambhat rifts. In *Saurashtra*, the largest ring complex covering 150 sq. km occurs in Girnar Hills near Junagadh. A central plug of diorite and monzonite with a ring of granophyre has the periphery of gabbro that is intruded by dykelets and veins of nepheline syenite, limburgite, monchiquite, kersantite and comptonite. A number of dolerite dykes radiates from the complex. Numerous circular, domal, concentric and arcuate bodies of rhyolite, pitchstone, trachyte and granophyre plugs are seen at Alech, Osham, Barda, Jetpur and Chamardi-Chowghat hills, and cuesta ridges from Dhari to Palitana hills. In *Khambhat rift and extensions along the West Coast*, alkaline complexes intrude the Deccan basalt at Mundwara near Mount Abu, Sarnu-Dandali near Barmer and Murud-Janjira south of Mumbai. Mundwara complex consists of three plutons having basic and acidic units. The basic unit comprises essexite, melteigite and mela-syenite. The felsic unit contains felspathoidal syenite and syenodiorite. The intrusive plugs are riddled with radial and concentric dykes, and carbonate veins. The Sarnu-Dandali complex consists of rhyolite, felsic tuff, alkali olivine basalt, hawaiite, trachyandesite, phonolite and nephelinite. These are intruded by felspathoidal syenite and alkaline mafic-ultramafic rocks and carbonatite. The Murud-Janjira alkaline complex south of Mumbai consists of lamprophyre and nepheline syenite dykes, plugs of ijolite and breccia pipes. Dykes and plugs of alkaline lavas and carbonatites are seen near Kawant and Siriwasan. Ambadongar (30 sq. km) carbonatite-alkali complex forms a unique ring structure containing several varieties of carbonatites and alkaline rocks. The carbonatite hosts a rich fluorite deposit. Phenai Mata Complex near Chhota Udepur consists of layered gabbro intruded by granophyre. The Deccan basalts of Kachchh contain numerous plugs, laccoliths and sheets of alkali basalt near Nakhatrana and Nana-Dhrubia. *Dolerite dyke swarms* of tholeiitic composition occur in Western Deccan Province and Narmada rift. They trend roughly N-S in the Western Deccan Province, and E-W in Narmada rift.

*Petrogenesis:* The dominant tholeiitic basalts are products of fractionation of primary picritic magmas generated at depths of 35-45 km. The picritic magmas were generated by partial melting of peridotite mantle in the Indian Ocean at the K-T boundary. The volcano-plutonic complexes are fractionated products of basaltic magma contaminated with continental crust or derived from enriched mantle source. Picrites and picritic basalts have resulted from 'delayed fractionation' or 'compensated crystal settling'. Polybaric fractionation has produced alkaline magmas. Separation of immiscible carbonate liquid from the alkaline magma has produced the associated carbonatites.

*Age:* Recent Ar-Ar and Re-Os isotopic dating shows the span of Deccan Trap activity to be between 63 to 66 Ma, corresponding to magnetic chrons of 31R to 28 N, with the peak between 65 and 66 Ma. These dates negate the earlier belief of a long duration as well as the later view of too brief a duration of one million years. These dates of Deccan lavas are consistent with similar dates from the intrusive volcano-plutonic complexes. The volcanism has occurred close to K-T boundary marking mass extinction and global climatic change. These catastrophic events are attributed either to bolide impact or to perturbation of carbon cycle by stupendous volcanism.

*Origin:* The mainstream view is that Deccan Trap originated when India drifted northward from Antarctica towards Asia, riding over the Reunion Plume with its large plume head (800 km diameter). The plume or hot spot caused the generation of underplated magmas in large magma chambers. The lavas were generated in Western Deccan Province and migrated to the south with the movement of Indian plate. An alternative minority view is that an old eclogitized oceanic crust trapped in ancient suture zones produced the voluminous Deccan lavas.

### *Inter-trappeans*

The strata/rocks that underlie the Deccan Traps are called Infra-trappeans. Strictly speaking, they can range in age from Precambrian to Upper Cretaceous, if the 'Traps' considered to be the lowest/oldest overlie the formations of those ages. However, in normal usage, only those strata, which are very close in age (usually Upper Cretaceous) to the Deccan Traps and are underlying them, are called Infra-trappeans. Lameta beds are the ones underlying the Traps and very close to them in age. The inter-trappeans are met with in parts of Gujarat (Anjar), Madhya Pradesh (Jabalpur), Maharashtra (Mumbai) and Andhra Pradesh (Naskal, Asifabad and Rajahmundry), besides in some of the offshore basins.

Inter-trappeans are those which lie in between any two trap flows. These are usually of terrestrial origin made up of sandstones, shale and even clay. More often they are lacustrine in origin and occasionally marine. They contain vertebrate, invertebrate and plant fossils. Among the vertebrates are the dinosaurs, fish, lizards and mammals. Amphibians and reptiles are found in the inter-trappeans of Andhra Pradesh. Numerous species of ostracods and foraminifera are reported, besides a few gastropods and bivalves. Charophyta, pollens and spores are also found in some of the inter-trappean strata.

Before the advent of radiometric dating and palaeomagnetic studies, the age of the Deccan Traps was estimated to range from Upper Cretaceous to Lower Eocene based on the ages assigned to the invertebrate and/or plant fossils in the strata immediately beneath what were then considered to be the oldest Traps and immediately above what were considered to be the youngest Traps. This meant that the duration could have been as long as 50 m.y. But now, mainly based on isotopic dating, the duration is considered to be a few million years around 65 Ma. Refined palaeontological data now indicates a Late Maastrichtian initiation of the Deccan volcanics at the top of the *Abathomphalus mayaroensis* planktonic foraminiferal zone (66.5 Ma) and an Early Paleocene termination at the base of *Globorotalina (A) praecursonia carinata* zone (61.2 Ma), duration of about 5 m.y., which is still more than that arrived at by isotopic dating.

An interesting observation associated with inter-trappean beds is the find of enriched iridium layers in Anjar (Gujarat) and Um Sohryngkew river section in Meghalaya. This is attributed to bolidal impact (exploding meteorite). Though mass scale extinction of dinosaurs is attributed to this impact, this view is contested.

### *Cenozoic*

Though comparatively of much shorter duration of about 65 m.y., the Cenozoic era witnessed quite a number of significant changes in patterns of sedimentation, structure and morphology of different sections of the country, more particularly in the extra-peninsular India. The latest subdivision of the Cenozoic is into Paleogene and Neogene Systems with Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene and Holocene as Series. In most of the available literature it will be found that the Cenozoic is divided into Tertiary (Eocene, Oligocene, Miocene and Pliocene) and Quaternary (Pleistocene and Holocene) and most of the descriptions of the geology are in terms of these time units.

Formations belonging to the Cenozoic occur as minor outcrops along certain sections of the Indian coast. They have been met with in force in the offshore regions. In the extra-peninsular region, an inner belt generally contains a Paleogene succession (Paleocene, Eocene and Oligocene) and an outer belt, Neogene succession (Miocene, Pliocene, Pleistocene and Holocene). Quaternary sediments of Pleistocene and Holocene never received the attention they deserved till the middle of the 20th century. Coastal alluvium, desert sands and Indo-Gangetic alluvium were all clubbed together under one category and left almost blank in all the geological maps. But the increasing occupancy of these tracts for human needs and exploration for water and construction materials, besides others, led to detailed investigations of the regions of this time period and now we have fairly good stratigraphic record of sediments of many regions among them. Apart from those in extra-peninsular India, rocks of Paleogene and Neogene are met with in Gujarat, Rajasthan, Meghalaya, Andhra Pradesh, Tamil Nadu and Andaman and Nicobar Islands. Whereas correlation of sediments within these regions was possible, dependable inter-regional correlation has been hampered due to absence of zone fossils. This was particularly noted in correlation of the Tertiary strata occurring in abundance in northeast India. Regional correlation of Himalayan Cenozoic has remained problematic because of restricted occurrence of fossils and marker beds, limitations of mineralogical compositions as a correlation tool and extensive lateral variation in lithofacies.

The breakaway Indian segment of Gondwanaland, after travelling over 7000 km came almost close to where it is now around 65 Ma. The northern margin collided with Asia and part of it got subducted. The collision resulted in faulting down to start with and subsequently successive diastrophic events pushed towards south large slices of sediments (nappes) in the Himalayan basin along extensive thrust faults, which have been named as Main Central Thrust, Main Boundary Thrust, Middle Siwalik Thrust and Himalayan Frontal Fault, as one proceeds from north to south. The sediments were tightly folded and split by faults and extensive intrusions of all forms followed including the welling up of ultrabasic rocks. This mixed assemblage –tectonised mélange – is described as the Indus-Tsangpo Suture almost at the northern boundary of the Himalayan province. Himalaya was uplifted in pulses during Late Cretaceous-Paleocene, Late Eocene, Middle Miocene (most pronounced of all) and Pliocene-Pleistocene. During Early Miocene (Aquitanian to Langhian) there was extensive intrusion of leucogranite between the Tethys zone and Lesser Himalaya right from Nanga Parbat region to Bhutan.

The Indus Suture Zone resulting from collision is dated around 51 Ma and the India – Asia collision in foothills belt around 47 Ma. Murree foredeep developed around 41 Ma and Siwalik foredeep around 16 Ma. It was in Middle Pleistocene that Sub-Himalaya, Indo-Gangetic and Brahmaputra basins formed. During Cenozoic there were major drops in sea level of 125 m, 80 m, 170 m and 150 m around 50 Ma, 35 Ma, 30 Ma and 10 Ma respectively, though in between there were sea level rises. These were recognized based on the unconformities, nature of sediments and microfauna found in offshore basins. Based on paleomagnetic record during 55 to 10 Ma, 1800 km and 2750 km of shortening has been estimated along the western and eastern sections of the Himalayan province, though the figures may be debatable.

Earlier, strata in Sind and Baluchistan in Pakistan were the type area for correlation of Tertiary in other parts of India, the horizons there known as Ranikot, Laki, Kirthar, Nari, Gaj and Manchar, extending from Paleocene to Pliocene in time. But now detailed information along with range in time is available on Tertiary rocks from Jammu and Kashmir to Uttarakhand. Because of investigations leading to exploration for hydrocarbons in parts of northeastern India, very detailed record on stratigraphy and structure of this region is available now. However, in the case of northeastern India, lack of invertebrate fossils had considerably reduced effective reliable correlation of strata in different regions, but now palynofossils are being extensively used for correlation. Andaman and Nicobar Islands seem to offer an almost continuous marine sequence of Late Mesozoic to Pleistocene age, the recognition facilitated by the occurrence of planktonic foraminifera. Data from deep-sea planktonic zones have aided in subdivisions of Late Cenozoic sequence in Andaman and Nicobar basin enabling a biomagneto-radiochronology.

Cenozoic is very well represented in Gujarat right from Paleocene to Holocene, both in surface and in subsurface, though minor hiatuses are met with in the sequences in Saurashtra and Kutch. In Rajasthan these occur in detached basins with marine and/or terrestrial sediments and in each of them only some periods within the Cenozoic are represented. Lignite occurs in the Palana-Ganganagar basin here. In Jammu they are represented by Hill Limestone, Charrat Stage and separated by an unconformity occur Murree and Siwalik sediments extending right from Eocene to Pleistocene. In Himachal Pradesh and Uttarakhand, Murree, Subathu, Dagshai, Kasauli, Siwalik and Alluvium (Older and Newer) represent the Cenozoic. In northeastern India these occur in different basins, affected tectonically to different extent but with many local names, but correlatable to the Group/Subgroup/Formation of Jaintia, Disang, Barail, Surma (Bhuban, Boka Bil), Tipam, Dupitila and Dihing. In Andaman and Nicobar Islands, part of Blair Formation and Archipelago Group belong to Cenozoic. Perusal of details of stratigraphic sequences in different parts of the Himalayan terrain presented by different authors would indicate that depending upon the geographical extent and thickness the same name will be used for a group in one place, but a formation in another.

As for life, there have not been mass scale extinction of biota or conspicuous generation of fresh species, animal or plant during this era. This has necessitated division of Cenozoic rocks based on relative proportions of molluscan fossils in a "period/ now Series" to the total assemblage of the same preserved in the entire era. Eocene contained less than 3.5%, Miocene up to 17%, Lower Pliocene up to 35 to 50% and Upper Pliocene up to 95% fossil forms of the living mollusca in their fossil assemblages. Though mollusca, echinoid, corals, crustaceans, bryzoans were present, foraminifera and ostracods were of importance in classification of strata in some regions to the level of stages and zones. They aided in the recognition of environments and climate. Palynoflora also came to play a major role during Cenozoic. Much angiospermous pollen commenced from Upper Cretaceous and extended up to Miocene.

Stratigraphers no longer ignore Quaternary, which records the history of the past 1.8 m.y. and witnessed the advent of man and also was subjected to neotectonic activity in the Himalaya as well as in parts of Peninsula. In most of the cases the sediments are unconsolidated – marine, fluviatile, lacustrine and aeolian besides residual deposits like laterite. Miliolite containing strata in Gujarat were one of the important horizons studied in detail. In central India the sediments are essentially fluviatile containing in a few places Toba ash bed as a marker horizon (~75,000 years). The primate *Homo erectus* made his appearance in the Pleistocene deposits here. Rajasthan contains latosols, evaporites and aeolian deposits. The Karewa Formation in Kashmir valley has received considerable attention because of its interesting lithological mix of fluviatile, lacustrine and aeolian deposits and subjected to tectonic upheaval.

Detailed mapping of the Indo-Gangetic plain, mainly aided by remote sensing, has brought to light a chequered history of this vast region caused by fluvial agent and affected by neotectonics. Volcanic activity during Quaternary is recognized in Andaman and Nicobar Islands, though Laccadive Islands owe their origin to submarine upheaval followed by coralline development. Laterite though extensive during the Quaternary in different parts, has also been found over older rocks in Gujarat. Laterite occurs over almost all types rocks igneous, sedimentary or metamorphic. It is now possible to date some of the Quaternary sediments based on many methods available such as C14 dating, thermoluminescence, palaeomagnetism, electron spin resonance, fission track and dendrochronology.

### *Siwalik Group*

The Siwalik Basin, extending from Potwar Plateau in Pakistan to Dafla-Subansari-Kimin belt in Arunachal Pradesh from the northwest to the east-northeast part of India, in an arc, with a convexity to the south, contains sediments belonging to the Siwalik Group of Middle Miocene to Lower Pleistocene within the Cenozoic. Sagging or bending down of the land in front of the Himalaya was mainly responsible for the formation of the Siwalik basin. The total thickness of the sediments in the basin is estimated to vary between 5000 to 7000 m. Nowhere the entire section can be observed. They are treated separately here because of their unique geographical position, deposition in a foredeep, consolidated and unconsolidated nature of sediments ranging from boulders, sandstones, shales, mudstones to clays and containing a rich assemblage, though in stray pockets only, of vertebrate fossils. These are mainly fluviatile and lacustrine deposits receiving sediments from the uplifted Himalaya through torrential streams. That there has been changes in the rate of sedimentation is inferred based on sudden changes in the nature and amount of sediments received from the north as well as from the Precambrian shield in the south. Towards the end, tectonic movements brought older strata from the north thrust over the different horizons in the Siwalik, bringing about many inversions in sequences, partly due to a series of strike faults.

Lack of clearly datable fossils led to the use of heavy minerals for correlation in the earlier studies. Concept of energy sequence was later introduced relating certain combination of heavy minerals among the sediments in a horizon as a consequence of uplift of certain sections of the provenance in the north. Thus the sediments along the foothills were divided into nine energy sequence units or en-seq, each characterized by distinct heavy mineral assemblage. More often the dates obtained based on the vertebrate fossils did not correspond with those obtained from plant fossils (leaf impressions). The problem is compounded by frequent facies changes in that a particular marker bed, say, red clay, in one area will be younger than the same red clay unit in a neighbouring area. Magnetic polarity stratigraphy provides now dependable results, based on which the Siwalik Group is considered to extend from 18.3 Ma to about 0.22 Ma.

The three fold classification of the Siwalik Group was made by Pilgrim based on comparison with the vertebrate fossil assemblages in Western Europe and is still generally followed. Sections of the three sub-groups of Lower (Kamlial and Chinji Formations), Middle (Nagri and Dhok Pathan Formations) and Upper (Tatrot, Pinjor and Boulder Conglomerate Formations) are met with in different places. There was glaciation during the Tatrot and Boulder Conglomerate times.

Elephants, giraffes, horses, hippopotamus and rhinoceros besides primates roamed over the terrain during this period. Fossil remnants of *Ramapithecus*, forerunner of early man, was found in the Siwalik strata.

### *Offshore Geology*

Investigations by Oil and Natural Gas Commission (now a Corporation) since the 1960s in the onshore and offshore basins have resulted in the accumulation of a wealth of data, particularly on the Mesozoic and Cenozoic sediments. The data has been obtained based on the borehole logs (lithology), seismic surveys (structure) and micropalaeontological studies. Some of the results have aided in filling up gaps in onland stratigraphic records. Precambrian basement was met with in a number of boreholes in the offshore basins of the east coast.

In the Bengal basin the Rajmahal Trap of Lower Cretaceous was the lowest to which most of the drilling was done. In Mahanadi basin the basement is Precambrian followed by basalts, equivalent to Rajmahal Traps, inter-trappean clays and Late Cretaceous sediments. In the Krishna-Godavari basin even Permo-carboniferous strata are present followed by Gondwana sediments above the Precambrian basement. Marine incursion took place in Lower Cretaceous. In the Palar and Penner basins, Lower Gondwana sediments possibly of glacial/marine origin were succeeded by near shore and marine sediments of Early Cretaceous. It overlies the Precambrian of Eastern Ghats and the sediments laid were of possibly Lower Gondwana, though marine incursion in the Cauvery (Kaveri) basin took place in Albian in Cretaceous and continued up to Lower Miocene. In most of the basins the sediments are found in the grabens. Sub-surface ridges and basins approximately trending NE-SW are quite common in the basins off the east coast of India.

In the Konkan-Kerala shelf off the West Coast, arenaceous and argillaceous sediments occur above the Deccan Traps followed by limestones. Whereas in the East Coast offshore basins there is a certain degree of continuation of some of the stratigraphic horizons present on land, in the West Coast, generally only patches of Neogene sediments are met with on land. In Mumbai offshore basin the sediments overlie Deccan Traps as well as Archaean basement in places. There is almost a continuous sedimentation extending from Paleocene to Pleistocene. Numerous horizons of limestone and calcareous shales occur in this basin. In the Kutch basin most of the drilling was done up to Middle Jurassic sediments. In the Andaman and Nicobar islands the sediments are from Cretaceous onwards and are associated with ophiolites.

Micropalaeontological studies, particularly those of planktonic foraminifera, ostracods and palynofossils in the Cretaceous and Cenozoic strata have brought to light zonal markers with biostratigraphic control. This has helped in the recognition of almost a continuous sequence of sediments during these times at least in the offshore, which is not to be seen onland.

The hydrocarbons are found either in structural or stratigraphic-cum-structural traps. Right now they are being exploited from the basins of Cambay, Bombay Offshore, Cauvery and Krishna-Godavari. With many private agencies also being now involved in exploration, it is hoped that in the near future many more hydrocarbon bearing horizons will be detected.

### *Morphology and Evolution*

Of late there has been an increase in the awareness of earth scientists to the potential of the study of the morphology and evolution of landforms both on a regional and local scale. The advent of remote sensing (both aerial photographs and imagery) as a tool considerably helped in proper evaluation of the landforms. An attempt is made in Chapter 13 to present only the highlights of some studies made on parts of India in this emerging field. The scenarios presented by the different regions in the country owe their origin to lithology, structure, climate and action of endogenic and exogenic agencies over time.

Most of the world's scenery and more so those of the southern continents, all of which contain a core of Precambrian shield, was carved during late Cenozoic time from a widespread landscape of low relief, subjected to aperiodic uplift. A smooth planation is often found upon highland, mountains as well as plateaus. In the continents of southern hemisphere (the erstwhile Gondwanaland) this ancestral landscape has been called Gondwana cyclic land surface, and its age has been determined as late Mesozoic (Jurassic – Cretaceous). This old land surface gets warped down both or on either side into the adjoining basins and sediments get deposited eroded from the uplifted land. This indirectly aids in inferring the age of the land surface.

This Gondwana landscape was broken up by the fragmentation of the Gondwanaland, when new coasts were roughed out by monoclinal warping, which created the outlines of the modern southern continents. This surface is thus of significance in relation to the hypothesis of continental drift/plate tectonics. The opening of the coasts of Africa, India, Brazil etc. took place in different times. With new coastlines generated, fresh base levels were created enabling the earlier landscape to be dissected. This process gave rise to landscapes of successively lower elevations, though all of them may not have been preserved in all the places.

Indian subcontinent also passed through similar cycles of uplift, warping, erosion etc., to give rise to a similar landscape particularly in peninsular India. In the Himalaya, however, the mountains were formed due to compaction and uplift of vast sediments laid in the Tethys Sea, and later folded, faulted and thrust in slices of large dimensions, mostly towards south. Subsequent glacial and fluvial erosion and neotectonics left behind the present complex topography, unlike that in peninsular India. Planation surfaces have been recognized in many parts of peninsular India and their extent, characteristics and possible ages arrived at. Broad correlation could be attempted only with those with comparable features in the neighbouring regions. Though it is possible that Jurassic landscape may exist somewhere in Peninsular India, most of them are only of Cenozoic age. The Indo-Gangetic plain, in between these two major landscapes, presents a conspicuous contrast in that it is a vast plain gently sloping due to east-southeast, essentially made up of sediments brought by the rivers from the north. Terraces and different forms due to fluvial erosion and deposition dot this entire landscape.

Apart from the planation surfaces of considerable varying extent, the other landforms that have evolved owe their origin to lithology, structure and tectonics of the region/area and the effect of exogenic agencies. Karst landscape, bornhardts (usually over granitic terrain), badlands (resulting from extensive erosion by rills of unconsolidated sediments) and dunes of various shapes are among these. Glacial landforms, both erosional and depositional, are confined to certain sections of Himalaya. Thus the Indian subcontinent presents landforms of almost all types present in most parts of the world.

# 3

# Cratons

## DHARWAR CRATON

### INTRODUCTION

The Archaean Dharwar Craton (Fig.3D-1), covering an area of about 4.5 lakh (0.45 million) km$^2$, is bounded to the south by the Pan-African Pandyan mobile belt (PMB); to the north by the end-Cretaceous Deccan Trap underlain and fringed by the Proterozoic (Purana) Kaladgi and Bhima basins; to the northeast by the Archaean Karimnagar granulite belt (KGB) adjacent to the Godavari graben that consists of Proterozoic Pranhita-Godavari basin and Phanerozoic Gondwana basin; to the east by the Neoproterozoic Eastern Ghats mobile belt (EGMB); and to the west by the Arabian Sea which separates India from Madagascar that contains a sliver of Dharwar craton. The concealed northern extensions of the craton under the Deccan Trap are believed to continue up to the Satpura mobile belt.

The Dharwar craton is one of the best-studied terrains of Peninsular India, and is renowned for its greenstone/schist belts, grey gneisses, charnockites and younger granites. The craton is divided into two tectonic blocks after Swami Nath et al. (1976), viz., the Western Block and the Eastern Block, renamed respectively as the Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) by Rogers (1986). The WDC and EDC are separated by the Chitradurga Shear Zone that is situated at the eastern margin of Chitradurga schist belt, not far from the western margin of Closepet Granite. The contact between WDC and EDC is not sharp, and there is a transition zone between the Chitradurga Shear Zone and Closepet Granite.

The grey gneiss complex covering the entire craton was formerly known by the omnibus term Peninsular Gneiss. In view of its critical differences in age, composition, mutual relation with the associated supracrustal rocks and geographic distribution in separate tectonic blocks, the term Peninsular Gneiss (>3000 Ma) is proposed to be restricted to WDC. The dominantly granitic terrain of EDC is called the Dharwar Batholith (>2500 Ma), after Chadwick et al (2000). The essential differences between WDC and EDC are summarised in Table 3D-1 (*see* Ramakrishnan, 1994).

**Table 3D-1.** Essential differences between Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC)

| Western Dharwar Craton (WDC) | Eastern Dharwar Craton (EDC) |
|---|---|
| 1. Dharwar schist belts – large, with volcanics, subordinate sediments | 1. Dharwar greenstone belts – narrow, with dominant pillowed basalts |
| 2. Peninsular Gneiss (>3000 Ma) basement having angular unconformity with the Dharwar marked by QPC. Basement gneiss inliers within schist belts | 2. Dharwar Batholith (2500-2700 Ma) intrusive on all sides. Diapiric gneiss domes common |
| 3. Three fold succession of : | 3. Three fold succession of : |
| (i) basalt-arenite-BIF | (i) Rare shelf sediments disrupted into screens at the belt margins |
| (ii) Shelf facies at the margin and homotaxial pillowed basalt-BIF in deeper waters | (ii) Pillowed volcanics, greywackes, BIF |
| (iii) Greywackes-BIF-volcanics | (iii) Felsic volcanics, volcanogenic conglomerate ('Champion Gneiss') |
| 4. Older sequence (Sargur Group) as narrow belts and enclaves, abundant in the south | 4. Older sequence (Warangal Group) mostly as enclaves in the northeast; and Salem Group (?) in the south |
| 5. Intermediate pressure (kyanite-sillimanite type) metamorphism | 5. Low pressure (andalusite-sillimanite type) metamorphism |

## Southern Granulite Terrain

The terrain occurring to the south of the orthopyroxene isograd (Fig.3D-2) that signals the arrival of granulite facies is generally known as the Southern Granulite Terrain (SGT). SGT corresponds to southern part of the Charnockitic Region of Fermor (1936) that is separated from his Non-Charnockitic Region along the orthopyroxene isograd called the Fermor Line by subsequent workers. Three prominent ductile shear zones of cratonic extent dissect the SGT, viz., (1) Moyar-Bhavani-Attur shear zone (MBASZ) in the north, (2) Palghat-Cauvery shear zone (PCSZ) in the middle, and (3) Achankovil shear zone (AKSZ) in the south. PCSZ marks a major terrain boundary that separates the Archaean Dharwar craton in the north from the Pan-African Pandyan mobile belt in the south. MBASZ delimits the marginal zone of the Pandyan mobile belt. AKSZ separates two different lithotectonic domains within the Pandyan

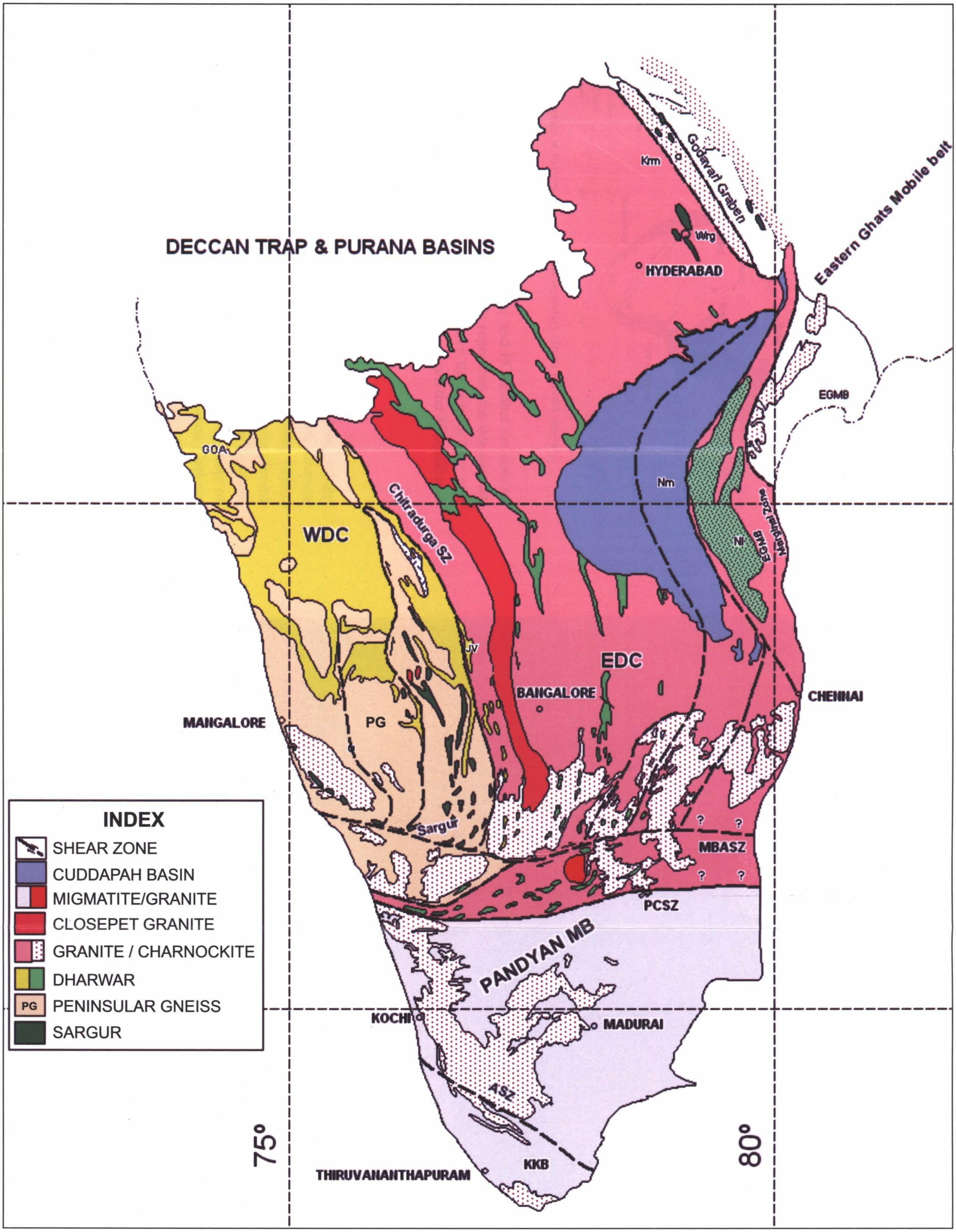

DECCAN TRAP & PURANA BASINS
Godavari Graben
Eastern Ghats Mobile belt
Km
Wrg
HYDERABAD
EGMB
GOA
WDC
Chitradurga SZ
Nm
Nl
EGMB
Nellore Zone
JV
EDC
BANGALORE
CHENNAI
MANGALORE
PG
Sargur
?
?
MBASZ
?
?
PCSZ
PANDYAN MB
KOCHI
MADURAI
ASZ
KKB
THIRUVANANTHAPURAM
75°
80°
INDEX
SHEAR ZONE
CUDDAPAH BASIN
MIGMATITE/GRANITE
CLOSEPET GRANITE
GRANITE / CHARNOCKITE
DHARWAR
PG
PENINSULAR GNEISS
SARGUR

**Fig.3D-1.** Essential features of Dharwar Craton. Abbreviations: SZ - Shear Zone; MB - Mobile Belt; PCSZ - Palghat-Cauvery Shear Zone; MBASZ - Moyar Bhavani Shear Zone; M - Moyar Shear Zone; B - Bhavani Shear Zone; ASZ - Achankovil Shear Zone; KKB - Kerala Khondalalite Belt; WDC - Western Dharwar Craton; EDC - Eastern Dhawar Craton; JV - Javanahalli belt; Nm - Nallamalai fold belt; Nl - Nellore schist belt; EGMB - Eastern Ghats Mobile Belt; Wrg - Warangal; Km - Karimnagar.

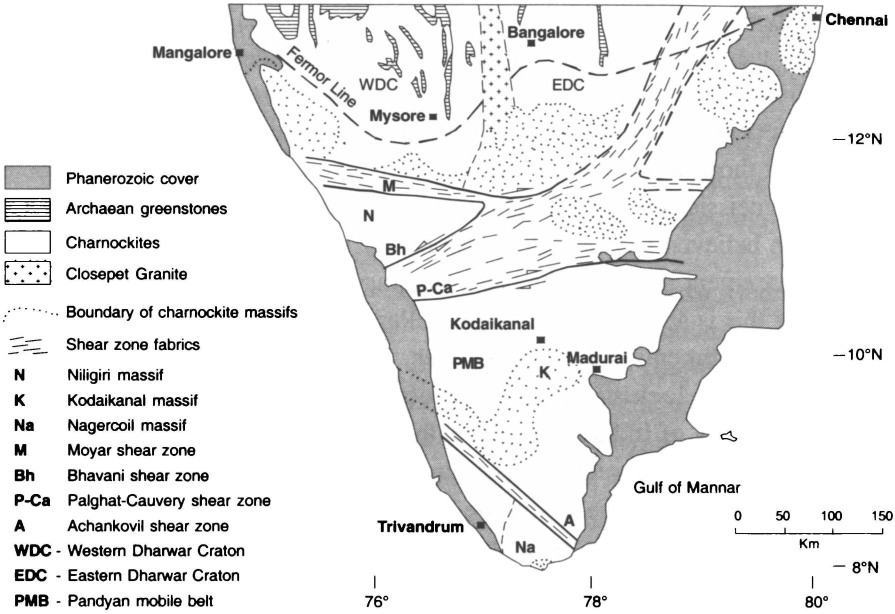

Mangalore
Fermor Line
WDC
Mysore
Bangalore
EDC
Chennai
—12°N
M
N
Bh
P-Ca
Kodaikanal
PMB
K
Madurai
—10°N
Gulf of Mannar
Trivandrum
A
Na
0 50 100 150
Km
— 8°N
76°
78°
80°
Phanerozoic cover
Archaean greenstones
Charnockites
Closepet Granite
Boundary of charnockite massifs
Shear zone fabrics
N Niligiri massif
K Kodaikanal massif
Na Nagercoil massif
M Moyar shear zone
Bh Bhavani shear zone
P-Ca Palghat-Cauvery shear zone
A Achankovil shear zone
WDC - Western Dharwar Craton
EDC - Eastern Dharwar Craton
PMB - Pandyan mobile belt

**Fig.3D-2.** Shear zones at the craton-mobile belt boundary (from various sources).

mobile belt. The terrain between the Fermor Line and PCSZ that consists of high-grade schists, orthogneisses and charnockites represents the deeper part of Dharwar craton. The description of the area between the Fermor Line and MBASZ will be dealt with here. The marginal zone between the MBASZ and PCSZ will be described under Pandyan mobile belt.

## Previous Studies

There has been a progressive evolution of thought on the regional geology of Dharwar craton following the developments in Europe and North America (Sambe Gowda and Srinivasan, 1979; Swami Nath and Ramakrishnan, 1981). The earliest was the Neptunian theory, which held that all rocks were formed in a primeval ocean. A.T. Christie in 1836 applied this theory to the Dharwar rocks and called them as "transitional rocks" of Werner, who was the father of Neptunism. Later, following the Huttonian theory of plutonism, Captain Newbold, between the years 1845 and 1850, described 'hypogene schists and gneisses' broken through by 'great outbursts of granite'. Developments in Canadian Shield geology, with emphasis on stratigraphy and basement-cover relations, held sway on Dharwar geology for many decades. R. Bruce Foote, by the turn of the nineteenth century, made a breakthrough by differentiating the 'crystallines' into 'Fundamental granitoid gneiss', unconformably overlain by the auriferous schistose rocks of 'Dharwar System'. The opposing school of W.F. Smeeth, in 1915-16, proposed that the gneisses were intrusive into schists and were therefore not 'fundamental' or 'basement'. Smeeth named the Fundamental gneiss of Bruce Foote as Peninsular Gneiss, in view of its extensive development in Peninsular India. It appears to be a truism in Dharwar geology that those who traversed first from the west (WDC) like Bruce Foote believed in gneissic basement, and those who traversed first from the east (EDC) like Smeeth believed in gneissic intrusion.

The basement problem has been dogging Dharwar geology for nearly a century and this is aptly described by E.H.Pascoe thus: "To be asked to regard the Dharwar sediments and lavas as everywhere the oldest rocks present is like being asked to look at a picture with no wall to support it". Stalwarts from Geological Survey of India like R.D. Oldham, T.H. Holland, C.S. Middlemiss and H. Crookshank, among others, joined the Bruce Foote-Smeeth debate. Eminent geologists of the erstwhile Mysore Geological Department like P. Sampat Iyengar followed the diktat of Smeeth, and this view held sway for long, the main advocates being C.S. Pichamuthu and B. Rama Rao. L.L. Fermor, while discussing the intrusive evidences, attributed them to the re-melting of the pre-Dharwar granitic crust and thus provided a new dimension to the problem. B.P. Radhakrishna, J. Swami Nath and GSI Officers, and B. Chadwick of Exeter University and his associates, finally established the basement nature of Peninsular Gneiss in WDC, despite the minority view of intrusive nature held by R. Srinivasan, K. Naha, S.M. Naqvi, some GSI officers and a few others.

W.F. Smeeth divided the schistose rocks of the Dharwar System into a lower hornblendic and an upper chloritic divisions. He visualised a progressive sequence of igneous intrusions into the Dharwar System, namely, the Champion Gneiss, Peninsular Gneiss, Charnockite and Closepet Granite. Smeeth also held a strange view that all schists were igneous and there were no sediments in Dharwar System. His bias was evident when he concluded, for example, that all Dharwar conglomerates were autoclastic and said "I...long for some one to find a simple satisfactory sedimentary conglomerate with nicely rolled water-worn pebbles". The sedimentary nature of the obvious lithologies like limestones, quartzites and conglomerates was ultimately established through the Herculean efforts of B. Rama Rao and C.S. Pichamuthu in the mid-thirties. The stratigraphic scheme of B. Rama Rao, consisting of a lower volcanic complex overlain by two sedimentary cycles separated by conglomerates, was still based on the Canadian model. C.S. Pichamuthu adopted Rama Rao's classification with the difference of including the Champion Gneiss as a unit within the Dharwar 'System', rather than as the earliest intrusive phase. B.P. Radhakrishna also adopted the idea of basal volcanics, and divided the overlying sediments into different units, but held that Peninsular

Gneiss was basement. A similar classification, but without volcanics at the base, was followed by S.V.P. Iyengar. Smeeth's classification was supported by a classic geological map on 1" to 8 miles (1:5,00,000 approx.) scale compiled by him and P. Sampat Iyengar in 1915. The classifications of Rama Rao, Pichamuthu and Radhakrishna were not backed by geological map of any scale.

With the advent of geosynclinal hypothesis in North America and Europe and its synthesis by J. Aubouin in 1965, R. Srinivasan and B.L. Sreenivas as well as B.R.C. Iyengar and others of Geological Survey of India modelled Dharwar stratigraphy on the basis of stages in the evolutionary cycle of a classical geosyncline. Even the Alpine-Himalayan analogy of ubiquitous thrusts was espoused in some models (e.g., S.P. Nautiyal). S.M. Naqvi proposed a classification involving many supracrustal units interleaved with gneissic units, forming schist-gneiss sandwiches as it were, based on presumed age differences and prevailing geochemical models of crustal evolution.

### Overviews of Dharwar Geology

Vast literature exists on the geology of Dharwar craton. Important books, papers and special issues of journals dealing exclusively with the broader aspects of Dharwar craton, are given below for reference: Bruce Foote (1888, 1889), Smeeth (1916), Vredenburg (1919), Sampat Iyengar (1920), Rama Rao (1940, 1962), Pichamuthu (1947, 1967), Swami Nath and Ramakrishnan (1981), Naqvi and Rogers (1983), Newton and Anderson (1986), Radhakrishna and Ramakrishnan (1990), Radhakrishna et al. (1990), Ravindra and Ranganathan (1994), Chadwick et al. (1997), Radhakrishna and Vaidyanadhan (1997) and Sarkar (2001).

## CLASSIFICATION

### New Classification

Dharwar geology took a great leap forward with fresh winds of change from the path-breaking work of C.R. Anhaeusser and the Viljoen brothers in the classical Barberton greenstone belt of Southern Africa, and of V.R. McGregor in the model high-grade terrain of West Greenland. The team work of geologists of Geological Survey of India led by J. Swami Nath, M. Ramakrishnan and M.N. Viswanatha in 1976 resulted in a holistic stratigraphic model which was backed by a 1:500,000 scale geological map published in 1981. The map also incorporated new data from regional remote sensing and airborne geophysical surveys. The essential features of this classification (Swami Nath and Ramakrishnan, 1981) are the following (Table 3D-2):

(1) Dharwar craton was divided for the first time into two tectonic blocks, WDC and EDC.

(2) Dharwar 'System' in WDC was grouped into two orogenic cycles separated in time viz., the older Sargur Group (3100-3300 Ma) and the younger Dharwar Supergroup (2600-2800 Ma), on the basis of the following criteria:

(i) Sargur and Dharwar successions are separated by deformed angular unconformities at Bababudan, Sigegudda, Jayachamarajapura (J.C.Pura) and Ghatti Hosahalli. Elsewhere (Hole Narasipura, Mayasandra), the two successions are folded together into parallelism during the younger Dharwar orogeny. Everywhere at the unconformity, Dharwar Supergroup shows coherent stratigraphy that is correlatable regionally, whereas Sargur Group is exposed at the same locality as a dismembered ensemble of variable rock types. At these places, the Sargur rocks are invariably veined by granitic material, whereas the adjacent Dharwar rocks remain unaffected and show no intrusive evidences. Furthermore, rare rock types not found in the Dharwar sequence, like bedded barite interlayered with fuchsite quartzite (as at Ghatti Hosahalli) and chromite-layered quartzite (as at Banavara), occur in Sargur Group near the unconformity (*see* Ramakrishnan, 1994).

(ii) Peninsular Gneiss forms the basement to Dharwar Supergroup and the contact is marked by a profound regional unconformity signifying prolonged denudation, following the cessation of Sargur

**Table 3D-2.** Simplified stratigraphy of Archaean Dharwar craton

| Age | Western Dharwar Craton (WDC) | | Eastern Dharwar Craton (EDC) |
|---|---|---|---|
| 2500-2600 Ma | Younger granite<br>(Chitradurga, Arsikere)<br>Charnockite | | Younger granite / gneiss<br>(Closepet and equivalents)<br>Charnockite |
| 2600-2800 Ma | Chitradurga Group<br>Bababudan Group | Dharwar Supergroup | Kolar Group<br>Yashwantanagar Formation |
| | - - - -unconformity- - - - | | - - - - - - - - - - - - - - - - - - |
| ~3000 Ma | Peninsular Gneiss | | Enclaves of older gneiss |
| 3100-3300 Ma | Sargur Group | | (?) Warangal Group<br>(?) Salem Group |
| 3300-3400 Ma | Gorur Gneiss | | Putative Basement |

orogeny (Ramakrishnan et al. 1976). The unconformity is defined by the presence of quartz-pebble conglomerate (QPC) which is locally uraniferous and sporadically contains 'shows' of copper and gold, like the better known QPCs of the world (e.g., Witwatersrand of South Africa).

(3) In EDC, younger granitoids dominate, with subordinate gneisses, together constituting the Dharwar batholith. The batholith intrudes wholesale the various units of Dharwar sequence (2600-2800 Ma).

(4) The transformation of gneisses into charnockites reported for the first time by C.S. Pichamuthu from Kabbaldurga in 1961, was shown to be a regional phenomenon that occurred at ~ 2500 Ma all along the amphibolite-granulite facies boundary in the craton (Ramiengar et al. 1978; Janardhan et al. 1982). This triggered a large volume of research into the genesis of charnockite, nature of the lower crust and evaluation of the craton-mobile belt relations in south India.

### Other Classifications

Two other major classifications that provided a different perspective are the ones by Pichamuthu and Srinivasan (1983) and Radhakrishna and Vaidyanadhan (1997). Pichamuthu and Srinivasan included Sargur Group (called by them as Nuggihalli Subgroup) at the base of Dharwar Group, with the whole sequence intruded by the migmatitic Peninsular Gneiss, followed by Charnockite and Closepet Granite. Since the distinction between Sargur and Dharwar has been amply clarified in the foregoing account, the contention of Pichamuthu and Srinivasan that the Sargur forms basal part of the Dharwar is no longer valid. Radhakrishna and Vaidyanadhan visualised that the Ancient Supracrustal Enclaves (Sargur type) were intruded by Older Gneissic Complex, and together overlain by Dharwar Supracrustals that are divided into a lower Kolar-type auriferous belts ('primary greenstones') and an upper Dharwar-type schist belts ('secondary greenstones'). Dharwar Supracrustals as a whole were shown as involved in successive intrusions of Younger Gneissic Complex, Charnockite and Closepet Granite. Recent geochronological data show however that Kolar-type and Dharwar-type supracrustals are contemporaneous, with no significant chronostratigraphic differences.

## WESTERN DHARWAR CRATON

Western Dharwar Craton (WDC) is occupied by vast areas of Peninsular Gneiss along with two prominent superbelts of Bababudan-Western Ghats-Shimoga and Chitradurga-Gadag belonging to the Dharwar Supergroup. In the southern part, there is a group of narrow, linear schist belts belonging to the older Sargur Group, like Hole Narasipura, Nuggihalli, Krishnarajpet (K.R.Pet), Mayasandra, Nagamangala and Melukote, as well as innumerable medium to high-grade schistose enclaves within Peninsular Gneiss, as at Sargur, Mercara (Madikeri) and their extensions in Kerala. Younger granites (~2600 Ma) like Chitradurga, Hosadurga, Arsikere and Banavara occur as isolated plutons in the gneissic country. An undated layered basic intrusion (Konkanahundi or Thagaduru) and a syenitic ring intrusion (Kunduru Betta) are also seen. Proterozoic basic dykes are also abundant. Rarely, Neoproterozoic granite (Chamundi Granite) and associated alkaline dykes are seen near Mysore and Harohalli. Syenite-carbonatite complexes (e.g., Dharmapuri) and kimberlites (e.g., around Cuddapah basin) are the other major manifestations of younger intrusive activity. Kimberlites will be discussed in Chapter 5.

The regional stratigraphy of WDC is presented in Table 3D-3. Brief description of various lithological units given in the table is presented below.

### Gorur Gneiss

The oldest gneiss in WDC is a suite of trondhjemitic gneisses with associated tonalites and granodiorites called as Gorur Gneiss. The gneiss yields whole rock Rb-Sr and Pb-Pb isochrons at 3300-3400 Ma. Still older SHRIMP U-Pb zircon and other isotopic model ages of 3500 to 3600 Ma in WDC do not relate to any known rocks, but are suggestive of earlier event(s).

Fresh outcrops of Gorur Gneiss are exposed in the stone quarries on either side of Gorur-Hassan Road (Fig.3D-3). These migmatitic TTG (tonalite-trondhjemite-granodiorite) gneisses consist of oligoclase, subordinate microcline, quartz and biotite or hornblende. Geochemical studies indicate that

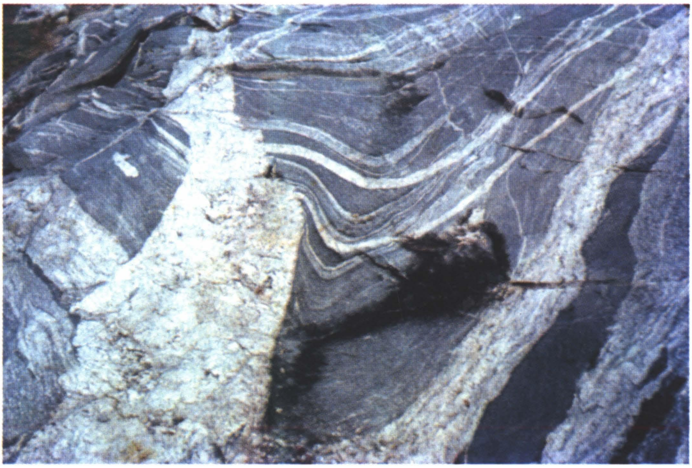


**Fig.3D-3.** Gorur gneiss near Hassan.

**Table 3D-3.** Regional stratigraphy of WDC (after Swami Nath and Ramakrishnan, 1981)

| | | | | |
|---|---|---|---|---|
| | | | Proterozoic mafic dykes | |
| | | | Charnockites (2500-2600 Ma) | |
| | | | Younger granites (2600 Ma) | |
| DHARWAR SUPERGROUP (2600-2800 Ma) | CHITRADURGA GROUP | Ranibennur Subgroup | Greywackes with BIF, polymict conglomerate, mafic-felsic volcanics | |
| | | Vanivilas Subgroup | Manganese and iron formations, stromatolitic carbonates, biogenic cherts, pelites, quartzites and polymict conglomerates (basin margin) | Mafic-felsic volcanics with BIF, phyllites (basin centre) |
| | | | Talya/Kaldurga Conglomerate = Metabasalts and siliceous phyllites of Jagar valley | |
| | | | Disconformity | |
| | BABABUDAN GROUP | Mulaingiri Formation | BIF with phyllites and rare ultramafic-mafic sills | |
| | | Santaveri Formation | Metabasalts, felsic volcanics (Galipuje felsite) ultramafic schists, layered basic complexes, siliceous phyllites, cross-bedded quartzite (Kaimara, Tanigebail) | |
| | | Allampura Formation | Metabasalts, gabbros, ultramafic schists, local BIF, phyllites, cross-bedded quartzite (Lakya) | |
| | | Kalasapura Formation | Metabasalts, gabbros, ultramafic schists, phyllites, quartzites, basal quartz pebble conglomerate (Kartikere Conglomerate) | |
| | | | Deformed angular unconformity | |
| | | | Peninsular Gneiss with trondjhemite-granodiorite plutons (>3000 Ma) | |
| | | | Intrusive / Tectonic Contact | |
| | SARGUR GROUP (3100-3300 Ma) | | Ultramafic-mafic layered complexes, tholeiitic amphibolites, komatiites, BIF | |
| | | | Quartzites, pelites, marbles and calc-silicate rocks | |
| | | | Intrusive / Tectonic Contact | |
| | | | Gorur Gneiss (3300-3400 Ma) | |

the gneisses are high-silica, low-alumina trondhjemites enriched in REE with less fractionated pattern (Ce/Yb < 7), and showing negative Eu anomaly. The gneisses are believed to have originated by low degree of partial melting of basaltic rocks in the lower crust or at the crust-mantle boundary. Their Pb and Sr isotopic compositions suggest they may have been mixed with older crustal protoliths of around 3800 Ma. Isolated occurrences of grey gneisses similar in age to Gorur Gneiss are found at Ammod Ghat (Goa), Tiptur, Gundlupet and other places.

The relationship of Gorur Gneiss with Sargur enclaves is uncertain, mainly because Gorur Gneiss is not mapped as a separate entity within the vast area of Peninsular Gneiss (~3000 Ma). Until this is done, the enclave suite in both the gneisses cannot be individually demarcated. This difficulty has led to a speculative suggestion that the enclaves may belong to more than one orogenic cycle. The available isotopic age data, however, indicate that the Sargur Group (3100-3300 Ma) may be younger than Gorur Gneiss (3300-3400 Ma).

### Sargur Group

Sargur Group occurs either as (1) linear mafic-ultramafic belts that progressively narrow down and break up into enclaves towards the south, or as (2) groups of enclaves scattered throughout the craton, but with a greater concentration in the south. It is a debatable point whether the narrow belts and enclave suites represent two different stratigraphic units. The lithological association is, however, remarkably similar in both, except that large layered ultramafic-mafic complexes form prominent ribs in linear belts due to their resistance to weathering. A composite stratigraphy for the belts and enclaves together is therefore appropriate, but will be *model dependent,* because the scattered nature of enclaves and restriction of one or two different rock types to each enclave lead to ghost stratigraphy that causes problems in correlation. If the quartzite-carbonate-pelite (QCP) suite is visualized as the base, the favoured choice is a continental interior or margin setting. If the ultramafic-mafic-BIF association is visualized as the base, an oceanic setting may be appropriate. The ultramafic-mafic units of certain greenstone belts are

**Table 3D-4.** Composite stratigraphy of Sargur Group (after Viswanatha and Ramakrishnan, 1981)

| | |
|---|---|
| | Peninsular Gneiss (~3000 Ma) |
| | - - - - - - - - - - - - - - Intrusive/ Tectonic Contact - - - - - - - - - - - - - - |
| Sargur Group (3100-3300 Ma) | Ultramafic-mafic intrusive complexes (Hole Narasipura, Nuggihalli) |
| | Cherts and BIF (Banded Iron Formation) |
| | Basaltic and komatiitic amphibolites, serpentinised komatiites |
| | Local marbles and calc-silicate rocks |
| | Garnet-biotite schists and para-gneisses (with kyanite, sillimanite, staurolite, graphite and corundum); rare cordierite-sillimanite-hypersthene gneiss |
| | Fuchsite quartzite with chromite layers and barytes beds |
| | - - - - - - - - - - - - - -Intrusive/ Tectonic Contact- - - - - - - - - - - - - - |
| | Gorur Gneiss (3300-3400 Ma) |

interpreted as ophiolites by some authors, but in Sargur they form layered complexes that clearly intrude the widespread pelitic schists. They are, therefore, more akin to the well-known layered complexes seen in the Archaean basins like Witwatersrand. Discovery of komatiites in South Africa by Viljoen and Viljoen (1969) led to the first report of komatiite in India by Viswanathan (1974) which acted as a trigger for numerous finds of komatiites in Sargur greenstone belts (*see* Jayananda, 2008). The composite stratigraphy (Table 3D-4) is therefore suggested for Sargur Group on the foregoing considerations:

### Sargur Schist Belt

The type area of Sargur Group is a zone of high-grade schist enclaves and narrow bands near Sargur town, situated 40 km southwest of Mysore city (Fig.3D-4). These rocks were known earlier as 'Sargur schists' belonging to 'Dharwar System'. The zone of enclaves extends from near Mysore to Kerala State (Indian Mineralogist, Special Issue, v.16, 1976), and up to Nanjangud in the east, with significant concentrations near Sargur and Gundlupet. Fresh outcrops of various lithologies were best exposed in the early 1970s in the canals of Kabini River near Sargur (Figs.3D-5a, b), and hence the name of Sargur Group. The high-grade schists, particularly the more susceptible lithologies like metapelites, are converted to paragneisses by migmatisation. Concomitant with medium to high-grade metamorphism, the schists are invariably invaded by granitoid veins.

Fuchsite quartzites, metapelites, carbonate- and calc-silicate rocks, probably denoting basal platformal suite, are well exposed as narrow bands in Jayapura, Sargur and Nugu Dam. Carbonate rocks are mostly marbles, and calc-silicate rocks contain amphiboles, diopside, garnet and some graphite. Metapelites and some quartzites are rich in garnet (almandine-pyrope), kyanite, sillimanite, staurolite, graphite and corundum. Rarely, cordierite-sillimanite-hypersthene rocks form very narrow bands. Metapelites locally contain semi-precious stones like garnet, star corundum, kyanite etc. Compositionally, the metapelites have high-Al and at places high-Fe as well, whereas some varieties are Mg-rich. The Cr, Co contents are higher than average, pointing to a provenance rich in sodic gneisses containing different ultramafic-mafic components.

Mafic-ultramafic rocks form one of the major components of Sargur schist belt. Mafic rocks are more abundant than ultramafic rocks and are commonly associated with iron formations in discrete bands and widespread enclaves. The ultramafic rocks are essentially serpentinites (meta-peridotites) and tremolite-actinolite-anthophyllite-chlorite-talc schists (meta-pyroxenites). Some of the mafic-ultramafic suites may form part of layered complexes such

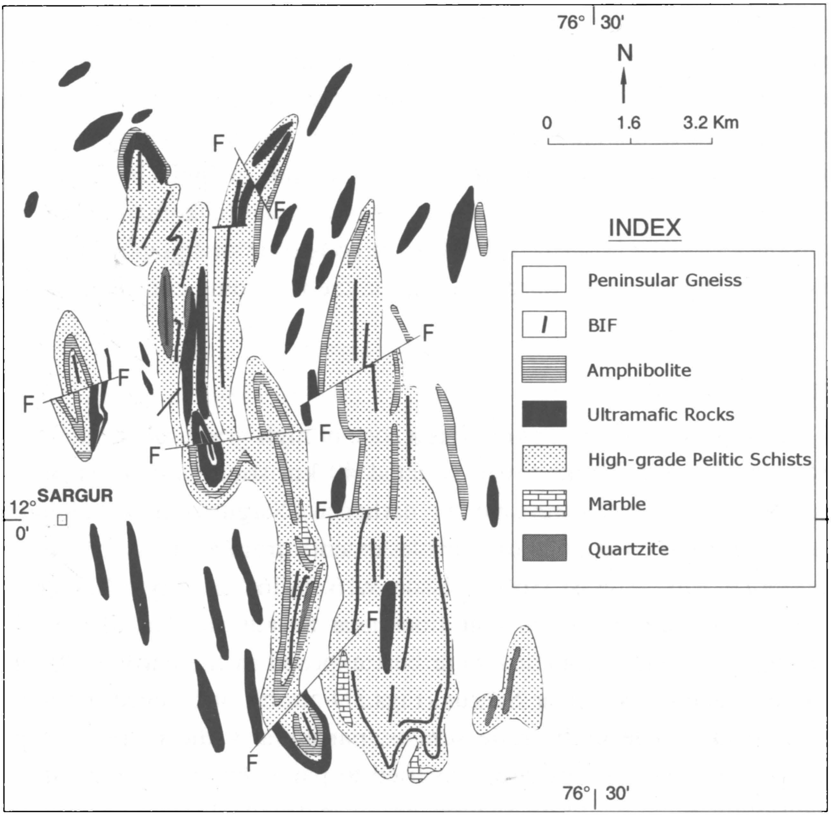


**Fig.3D-4.** Geological map of Sargur schist belt near the type area of Sargur (after Viswanatha and Ramakrishnan, 1981).

as the chromiferous ultramafics at Sindhuvalli and anorthosite layers in gabbros at Hullahalli/Kurihundi (near Nanjangud) and Gundlupet. Some of the ultramafics may be komatiitic flows as reflected in the mineralogy and geochemistry, although textural evidence of their extrusion is lacking in Sargur schist belt. Amphibolites and pyribolites containing two pyroxenes, amphiboles and garnet are the main basic rocks. The basic rocks show typical tholeiitic trend and are essentially low-K tholeiites that are olivine to hypersthene normative. In geochemical discriminant diagrams, they straddle the field of oceanic to calc-alkaline basalt. Iron formations belong to silicate and oxide facies and contain quartz, magnetite, garnet, hedenbergite and hypersthene. The iron formations, though largely chemical precipitates, contain a noticeable admixture of fine clastics.

*Structure:* The earliest recognisable structure in the narrow linear belts of Sargur Group is widespread schistosity parallel to the bedding, intrafolial folds and migmatitic banding. The second phase of deformation has given

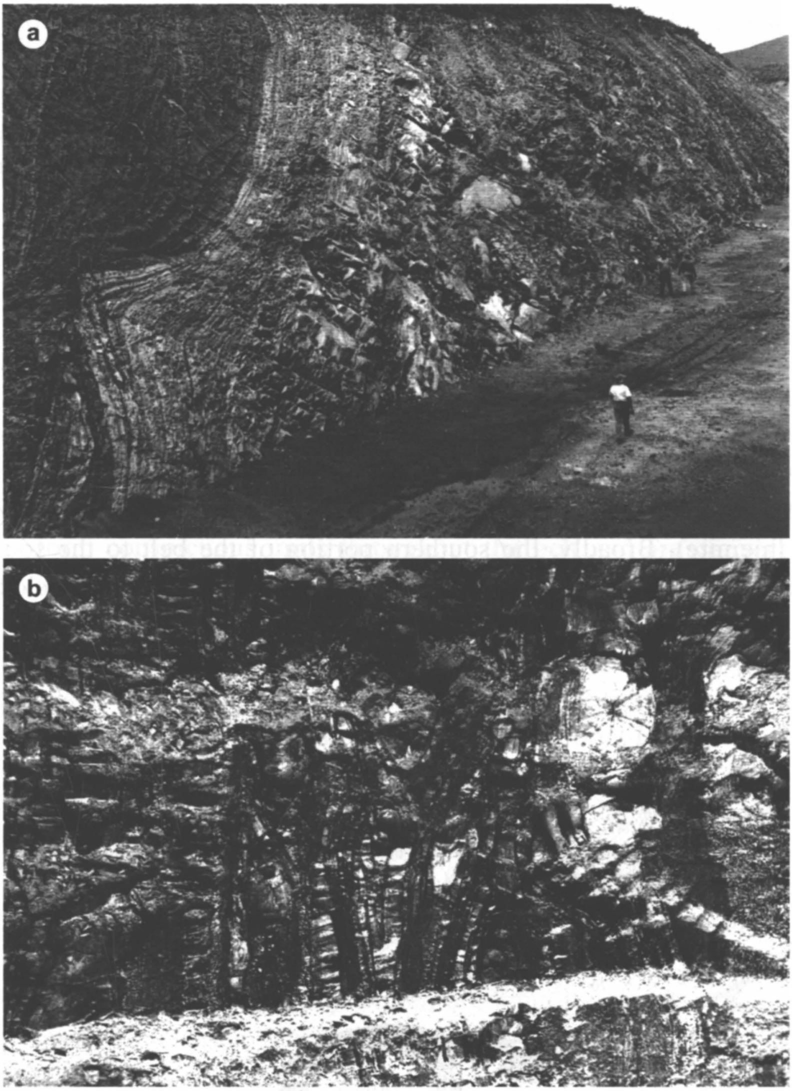


**Fig.3D-5.** (**a**) Kabini canal section near Motha showing boudinaged BIF in the left with metapelite, sillimanite quartzite and amphibolite within the weathered gneiss. (**b**) Kabini canal section near Thoravalli with boudinaged pyribolites (Viswanatha and Ramakrishnan, 1976).

rise to upright, tight to isoclinal folds, causing preservation of schists in synformal keels and antiformal arches. The third deformational phase has refolded the folds of second generation on northerly axes. Late shear zones marked by mylonites are common.

***Manantavadi (Wayanad) Schist Belt:*** The Sargur enclaves containing similar lithology extend via Sultan Battery, Manantavadi and Iritti to Talipparamba in Kerala and are delimited by the Bavali fault at the western extension of MBASZ. Several bodies of gabbro and pyroxenite intrude the Sargur schists that are locally labelled as Wayanad Group.

***Kasaragod Schist Belt:*** Another parallel belt in the north containing similar lithology occurs as the extension of schist enclaves from Mercara (Madikeri), Sulliya and Jalsur to Kasaragod.

## Hole Narasipura Schist Belt

This trident-shaped schist belt is of special interest for regional geology because the Sargur and Dharwar successions are not only well exposed in the same belt, but also are deformed and metamorphosed together during the later Dharwar orogeny (Fig.3D-6). The trident shape of the schist belt is due to the deflection of schists around bosses of Mavinkere Granodiorite (Halekote Trondhjemite). Broadly, the southern portion of the belt to the south of Hemavathi River belongs to Sargur Group, and the northern portion belongs to the Bababudan Group of Dharwar Supergroup. The contact between the two successions is conformable due to co-folding. A quartz pebble conglomerate known as Tattekere conglomerate, closely intercalated with amygdular meta-basalt at Tattekere, occurs at the contact and marks the base of the Dharwar

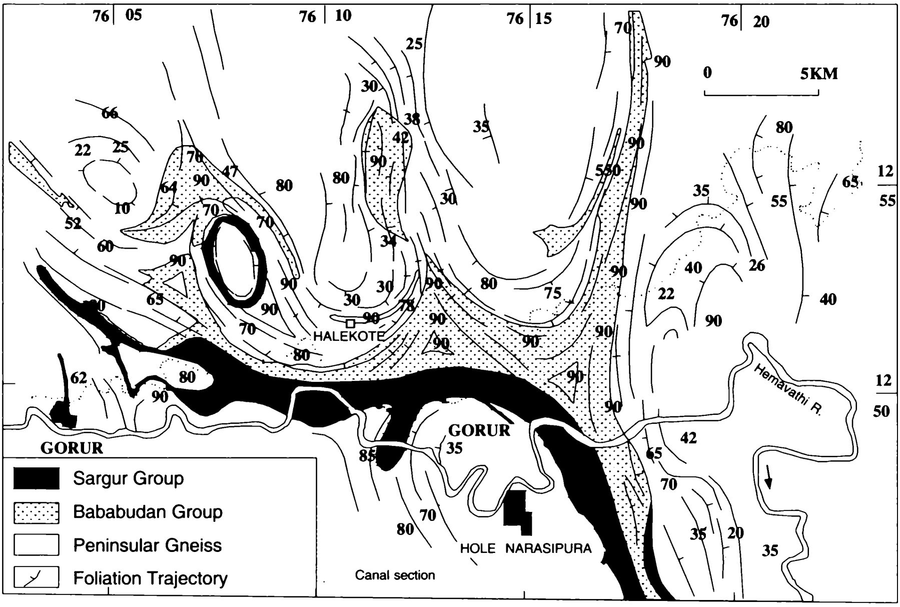

76 05
76 10
76 15
76 20
0
5KM
12 55
12 50
HALEKOTE
GORUR
GORUR
HOLE NARASIPURA
Hemavathi R.
Canal section
Sargur Group
Bababudan Group
Peninsular Gneiss
Foliation Trajectory

**Fig.3D-6.** Structural concordance between Sargur and Dharwar sequences in the Holenarsipura belt (modified from Bouhallier et al. 1993; with permission from Elsevier).

succession. The conglomerate is extensively sheared and so has been mistaken by some for autoclastic or crushed conglomerate having no stratigraphic value, but its strike continuity in the north with the uncrushed Kumkumna Hosur conglomerate having clear arenaceous matrix and heavy mineral composition, confirms its sedimentary origin (*see* Chatterjee and Das, 2004).

### *Sargur Group*

In Hole Narasipura schist belt, Sargur Group consists of kyanite-staurolite-garnet-graphite-mica schists, amphibolites, komatiites and minor BIF, with rare calc-silicates and quartzites. Komatiites are mostly metamorphosed (serpentinized peridotites) and have no primary mineralogy. Pillow structures are reported from them. They show relict spinifex texture and comparable chemistry to the well-known komatiites from Archaean greenstone belts. Pelitic schists form conspicuous units throughout the belt and are converted to paragneisses at the margins of schist belts by felspathisation and granite veining. Nodular fibrolite is found in some pegmatite veins. The pelitic schists are intruded by a prominent layered ultramafic-mafic complex consisting of serpentinised peridotite with lenses of meta-dunite, tremolite-actinolite-anthophyllite-talc-chlorite schists with lenses of chlorite-magnetite-epidote schists (meta-pyroxenites), and gabbroic amphibolites (±garnet). Lenticular meta-anorthosites (±garnet) are found within the layered complex at several places. Layers of chromite are seen in the meta-ultramafics as seen at Sravanur and YHR (Yenneholerangana) Betta. The ultramafic rocks host veins of amphibole asbestos as well as vermiculite and corundum at the contact of pegmatoid veins. On the whole, the schists constitute an interesting petrological museum. Beryl and columbite-tantalite are associated with pegmatites that intrude the schists.

Detrital zircons from the garnet-mica schists yield direct evaporation age of ~3300 Ma and SHRIMP U-Pb age of 3100 to 3300 Ma, with some values around 3600 Ma reflecting the protolith age of the source rocks. Ultramafic-mafic rocks yield Sm-Nd model age of ~3100 Ma. The anorthosites of the layered complexes also yield Rb-Sr age of ~3100 Ma. These dates help to fix the younger limit of Sargur Group at ~3100 Ma. The ~3300 Ma ages suggest derivation of zircons from Gorur Gneiss and marks the older limit.

### *Bababudan Group*

Bababudan Group in Hole Narasipura schist belt commences with Tattekere conglomerate, overlain by cross-bedded quartzite-amygdular basalt association as seen in Modulgudda. The micaceous portions of Tattekere conglomerate show higher metamorphic grade with the presence of staurolite and kyanite. The basalts are amphibolites at the margins and greenstones (epidiorites) in the core portions. Mostly they are amygdular, but are rarely pillowed. Rare quartzofelspathic veins locally intrude the amphibolites at the sheared margins of the belt. Metabasaltic amphibolites yield Sm-Nd isochron age of 2600 Ma. Garnetiferous mica schist and chloritoid-garnet schist are the pelitic units seen in association with metabasalts and quartzites. Acid volcanic rocks containing opalescent quartz set in a sericite-chlorite-quartz matrix, form interbeds in the basaltic sequence at Kyatankere. These volcanics surprisingly yield SHRIMP U-Pb zircon age of 3300 Ma, which is perhaps a reflection of the age of surrounding basement gneisses (Gorur Gneiss?) from which the acid volcanics have probably derived their xenocrystic zircons. BIF forms a prominent band on top of hills in the eastern arm of the schist belt. A polymict, granite-clast conglomerate (Sannenahalli conglomerate, Doddagudda conglomerate) exposed in the eastern arm, is similar to Kaldurga conglomerate occurring at the base of Chitradurga Group of Dharwar Supergroup in the Bababudan belt. Ultramafic schists are seen as minor concordant layers or sills in the eastern arm.

### Nuggihalli Schist Belt

The ultramafic-mafic suite of Nuggihalli belt represents a differentiated intrusion of serpentinised peridotite with lenses of altered dunite, tremolite-actinolite-cummingtonite-anthophyllite-talc-chlorite-magnetite schists (metapyroxenites), and gabbroic amphibolites (±garnet) with layers of anorthosites. Anorthosite occurs also as a dyke at Jambur.

The serpentinite contains many seams of chromitite (Fig.3D-7a), which are sporadically mined. Chromitite seams contain traces of platinoids. Marginal gold occurrences and chrysotile as well as amphibole asbestos are seen in ultramafic rocks. Minor corundum and vermiculite are found in pegmatitic contact zones in the ultramafics. Some of the ultramafic rocks are described as pillowed, but they appear to be more like spheroidal weathering features. Rare instances of ultramafic komatiite with spinifex texture are reported from outside the layered complex. The gabbroic rocks contain titano-magnetite 'reefs' that were explored for titanium and vanadium. They also host marginal deposits of copper with minor nickel, as well as rare semi-precious corundum in titano-magnetite.

The country rocks, into which the ultramafic-mafic suite is emplaced, are garnetiferous amphibolites (metabasalts?), garnet-staurolite-kyanite-mica schists, fuchsite quartzites, calc-silicate rocks, and BIF with grunerite and garnet. Zircon Pb-Pb age of mica schists is ~3200 Ma and of TTG gneiss is

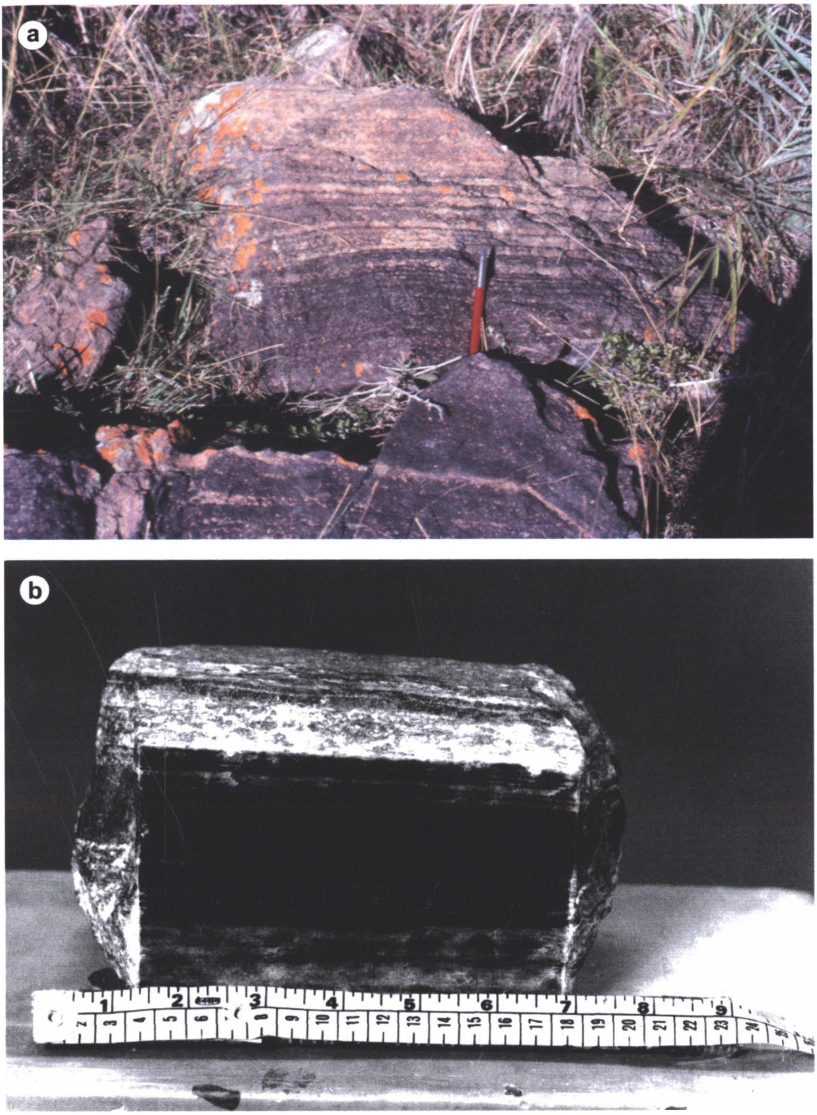


**Fig.3D-7.** (**a**) Chromite seams in serpentinite near Tagadur, Nuggihalli belt. (**b**) Chromite layers in fuchsite-kyanite quartzite, Banavara.

3000-3100 Ma (Bidyananda et al. 2003). The southerly extension of Nuggihalli belt is called **Kempinkote belt** that hosts minor gold occurrence.

**Aladahalli Belt:** The Aladahalli (or Gandashi) belt was recently located by aeromagnetic surveys and explored for copper. This is an arm branching off from Nuggihalli belt passing through Gandashi and is marked by pelitic schists, cordierite-anthopyllite rocks, amphibolites and chromite-bearing ultramafics.

### Other Ultramafic-Mafic Belts of Sargur Group

There are prominent ultramafic-mafic belts that form conspicuous layered complexes occurring within the schist belts of Sargur Group. The layered complexes are characterized by the presence of anorthositic differentiates in gabbro, chromite lenses and disseminations in serpentinised ultramafics, and titano-magnetite 'reefs' in gabbros. Subordinate quantities of peridotitic komatiites, and amphibolites having a compositional range of high-Al, low-K tholeiites, high-Mg basalts and basaltic komatiites are seen in these belts. These ultramafic-mafic belts form an elongate arcuate zone about 350 km long from Nanjangud to Shivani in the gneissic region between the Chitradurga-Gadag and Bababudan-Shimoga schist belts (Ramakrishnan et al. 1978). Among the important ultramafic-mafic schist belts are those of Krishnarajapet, Hadanur, Melukote, Nagamangala, Kalyadi, Banavara and Antharaghatta. There are similar belts at Jayachamarajapura (J.C.Pura), Ghatti Hosahalli and Mayasandra situated very close to and juxtaposed with the main schist belt of Chitradurga and these will be described under the main Chitradurga-Gadag belt.

**Krishnarajpet (K.R.Pet) Belt:** This is a spindle-shaped belt situated to the south-east of Hole Narasipura belt and has similar lithology and geological setting.

**Hadanur Belt:** A string of ultramafic-mafic enclaves south of Nuggihalli belt and parallel to K.R. Pet belt forms the small belt of Hadanur.

**Melukote** and **Nagamangala Belts:** These are also known for ultramafic-mafic rocks and pelites. Nagamangala and K.R.Pet belts contain marginal grade gold.

**Kalyadi belt:** This belt occurs to the southwest of Arsikere and is made of cherty quartzite that hosts a marginal copper deposit. Numerous enclaves of ultramafic schists, some with spinifex texture, are seen in the vicinity. Some of them contain corundum and sillimanite in the contact zones with intruding pegmatites. Pelitic schists and paragneisses containing garnet, staurolite and kyanite occur as enclaves closeby.

**Banavara belt:** This belt containing the spectacular chromite-layered fuchsite-kyanite quartzite (Fig.3D-7b) is exposed in the strike extensions of Aladahalli belt amidst gneisses on the Bangalore-Honnavara Highway near Banavara. Zircons from the quartzites of Banavara belt have given SHRIMP

U-Pb ages of 3100 to 3300 Ma, similar to that of Hole Narasipura belt. Banavara belt, together with the extensions of Nuggihalli and JC Pura belts, continues up to Shivani (called locally as **Shivani belt**) near Shimoga schist belt. Such a composite belt of enclaves called **Antharaghatta belt,** contains both layered mafic-ultramafic complexes and spinifex textured and pillowed komatiites in abundance.

## Peninsular Gneiss

Grey gneisses of shield areas consist of polyphase migmatites and homophanous granitoids. They are differentiated in some areas by the use of basic dyke markers, but where the dykes are absent, geochronology is a valuable tool for classification into different tectonic cycles. Peninsular Gneiss in WDC consists of three main crustal accretion events, namely at 3300-3400 Ma, 3000-3100 Ma and 2500-2600 Ma. The first and third events are sporadic in WDC, whereas the second event very pronounced and widespread.

Peninsular Gneiss consists of two principal components viz., (i) multiple migmatites of TTG composition and (ii) homophanous trondhjemite to granodiorite plutons intrusive into the migmatites (Figs.3D-8a, b). Both components show indistinguishable ages of >3000 Ma by different isotopic systematics in the vicinity of Hassan, Chikmagalur and Chitradurga. In the region around Hole Narasipura to Shivani and Nuggihalli to Holalkere, the migmatitic leucogneisses are riddled with enclaves of ultramafic-mafic rocks. The gneisses have very little sedimentary contribution as evidenced by the lack of rounded zircons, low Cr and no normative corundum. The TTG gneisses show typical calc-alkaline differentiation trend. They are believed to have formed by the partial melting of a mafic source in the deep crust, together with melting of pre-existing crust, accompanied by metasomatism of lithophile elements around 3000 Ma. This has depleted the crust in heat-producing elements, which caused the sporadic incidence of granitic magmatism (e.g. Arsikere Granite) at ~2600 Ma.

The TTG gneisses also occur as basement inliers within the Chitradurga and Shimoga schist belts. The gneissic inliers have concordant foliations at the contact with the schist belts, but are overlain by basal sediments and conglomerates. Some authors interpret these inliers as mantled gneiss domes, but the lack of intrusive effects at the contact, intact preservation of older enclaves in the inliers, and retention of basement ages of ~3000 Ma show that the gneisses, though deformed together with the overlying schists, are basement inliers rather than intrusive or remobilised mantled gneiss domes.

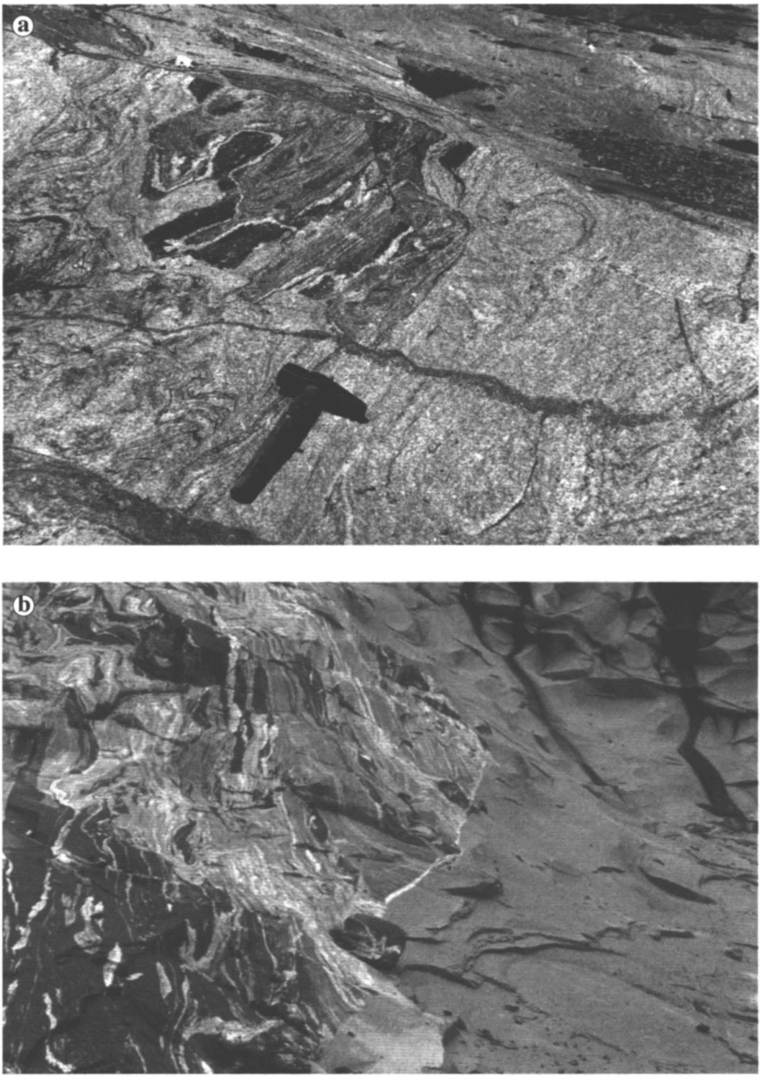


**Fig.3D-8.** (**a**) Older migmatite enclave in a nebulitic granodiorite near Hirisave (**b**) Banded gneiss intruded by homophanous granodiorite, Brahmanayakandurga.

Typical trondhjemite-granodiorite plutons are the Chikmagalur granodiorite intruding Kalasapura gneisses, Halekote trondhjemite intruding Hassan gneisses, Karadi trondhjemite intruding Tiptur gneisses and many such intrusions in the west of Chitradurga schist belt. The plutons sharply cut across the gneissic banding in all cases (Fig.3D-8b). At places they deflect the schist belts around them by a kind of buoyancy during ascent or by fold interference in schists around a rigid basement dome. The gneisses and diapiric plutons may form plutonic belts of a 3000 Ma old batholith, with intervening Sargur ultramafic belts.

## Dharwar Supergroup

Dharwar Supergroup is developed in force in WDC where it is divided into a lower Bababudan Group and upper Chitradurga Group. The supergroup is exposed in two large schist belts that may be called superbelts viz., (1) Bababudan-Western Ghats-Shimoga and (2) Chitradurga-Gadag. To the south of these superbelts, smaller belts like Sigegudda and the northern part of Hole Narasipura belt expose the rocks of Bababudan Group.

### Bababudan-Western Ghats-Shimoga Superbelt

This superbelt is spread over an area approx. 300 km long and 100-150 km wide, with schistose rocks occupying about 30000 km$^2$ and the remaining 15000 km$^2$ occupied by the intervening basement of Peninsular Gneiss. Shimoga belt is linked to the Chitradurga belt through a small bridge of schists cusped between domal areas of gneisses near Harappanahalli (Chadwick et al. 2003, 2007). The various constituent belts of this superbelt are described below.

#### *Bababudan Schist Belt*

This squarish belt occupies an area of 2500 km$^2$ and is the type area for Bababudan Group (Fig.3D-9). The base of the Bababudan Group is marked by

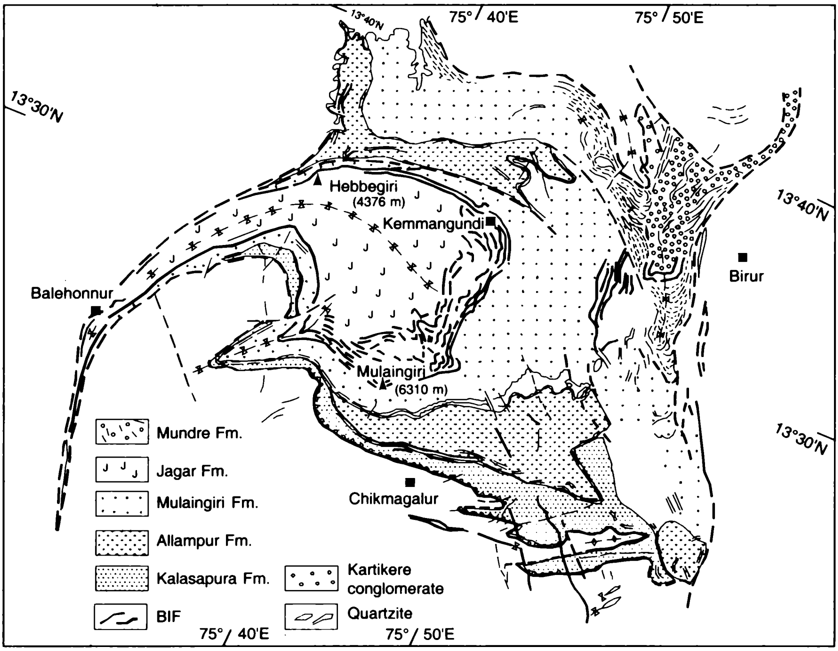

13°40'N
75°/40'E
75°/50'E
13°30'N
Hebbegiri
(4376 m)
Kemmangundi
Balehonnur
Mulaingiri
(6310 m)
Birur
13°40'N
13°30'N
Chikmagalur
Mundre Fm.
Jagar Fm.
Mulaingiri Fm.
Allampur Fm.
Kalasapura Fm.
BIF
Kartikere conglomerate
Quartzite
75°/40'E
75°/50'E

**Fig.3D-9.** Geological map of Bababudan schist belt (Chadwick et al. 1985).

a prominent but thin horizon of quartz-pebble conglomerate (Fig.3D-10a), which marks a profound unconformity between the basement of TTG gneisses and the Dharwar Supergroup. Bababudan Group is dominantly made of three successive cycles of amygdular metabasalts (Fig.3D-10b) interbedded with cross-stratified quartzites (Fig.3D-10c), capped by a prominent BIF, which is mined for iron ore. Such a lithological association has a typical Proterozoic aspect, but due to diachroneity in crustal evolution, this ensemble forms part of an Archaean schist belt that has similarity with the Archaean Witwatersrand basin of South Africa. The metabasalts of Bababudan Group are low-K tholeiites with carbonate and muscovite bearing spilites seen in the upper part (Santaveri Formation). The metabasalts show flat HREE and moderate LREE enrichment indicating a mantle source enriched in lithophile elements. Negative Eu anomalies suggest plagioclase fractionation, whereas the mafic-rich portions result from fractionation of pyroxene and olivine. The metabasalts are dated by whole rock Rb-Sr and Sm-Nd isochrons of about 2700-2800 Ma. Black phyllites associated with BIF give SHRIMP U-Pb age of ~2700 Ma.

### *Sargur Enclaves*

A string of Sargur enclaves aligned N-S to NNE-SSW underlies the E-W trending basal conglomerate of Bababudan Group (Chadwick et al. 1981; Ramakrishnan and Viswanatha, 1987). In Kalasapura ghat section, the enclaves are amphibolites, ultramafic schists and BIF, whereas in the Belavadi section fuchsite quartzites and quartz-mica schists dominate with subordinate amphibolites and ultramafic rocks. In contrast to the Bababudan tholeiitic lavas, the Sargur metabasics in this area are high-Al basalts.

### *Bababudan Group*

*Kartikere Conglomerate*: The basal quartz-pebble conglomerate (QPC), named the Kartikere conglomerate (Fig.3D-10a), extends discontinuously for 40 km at the southern margin of the schist belt and is exposed in a linear array of hillocks rising from the plains. The QPC consists of subrounded to subangular pebbles of vein quartz and rare fuchsite quartzite of the underlying Sargur Group.

A thin bed of quartz-muscovite schist underlies the conglomerate and may represent a regolith or sheared granitoid basement. The conglomerate grades into cross-bedded quartzite and is mostly clast-supported, with arenaceous matrix containing detrital grains of ilmenite, pyrite and other sulphides, uraninite, zircon, tourmaline, rutile, epidote, chromite and felspar. Zircon morphology indicates that it is derived from the Chikmagalur

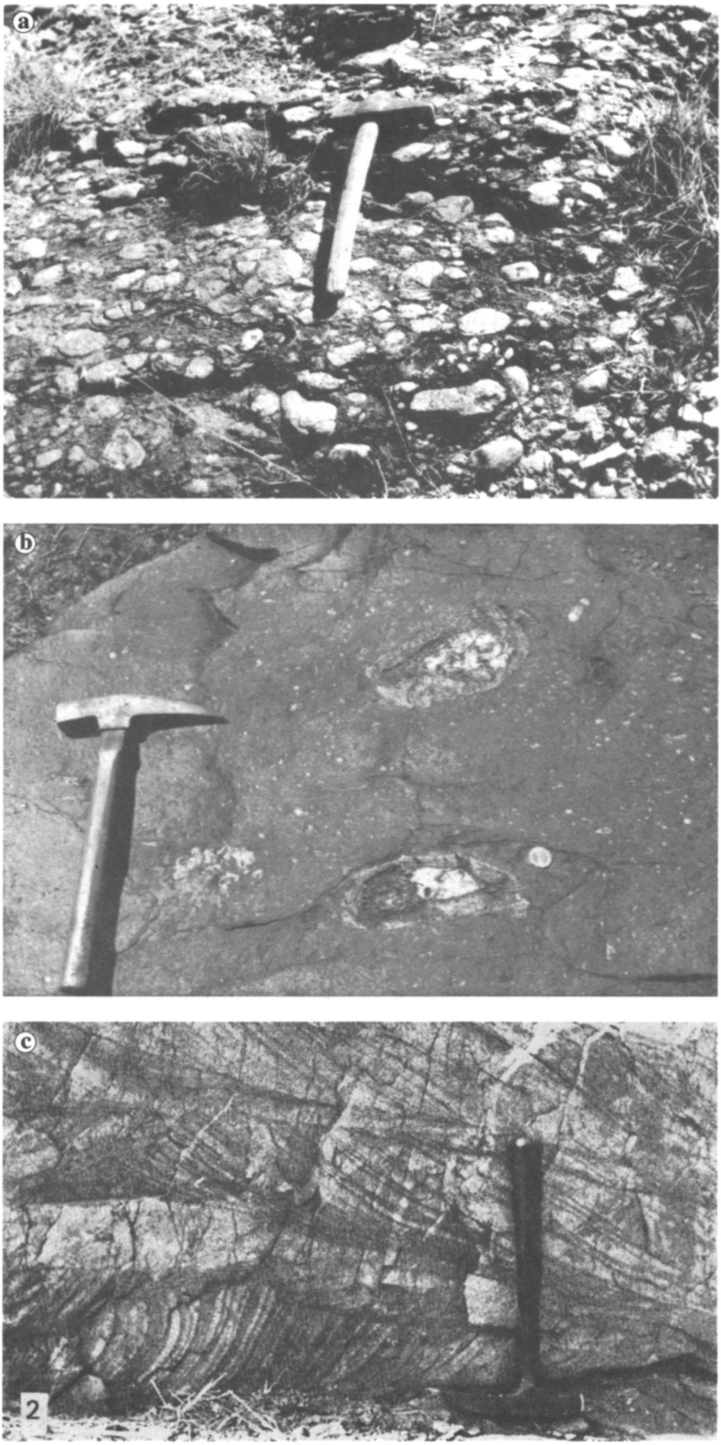


**Fig.3D-10.** (**a**) Basal quartz pebble conglomerate (QPC) near Kalasapura. (**b**) Amygdular metabasalt at Sindigere. (**c**) Cross bedded quarzite on Chikmagalur-Kadur road, (Fig.10c, Courtesy: R. Srinivasan).

granodiorite basement. The conglomerate has been explored for uranium, copper and gold, but the grades are subeconomic. In terms of geological setting (but not the grade), these conglomerates are comparable to those of Witwatersrand of South Africa, Blind River of Ontario in Canada, Jacobina of Brazil and Nullagine of Australia.

*Kalasapura Formation*: This formation is essentially made of amygdular metabasalt (Fig.3D-10b) having amygdales filled with quartz and chlorite. Some metabasalts are massive and others are schistose, containing actinolite, epidote, plagioclase, carbonate and opaques. Chlorite-quartz phyllites with rare chloritoid, garnet and kyanite occur locally. BIF with garnet and grunerite also occurs locally.

*Allampur Formation*: This formation consists principally of metabasalts with thin intercalations of phyllite, quartzite and local BIF. The intercalations of arenites contain load casts, armoured mud balls, dish and pillar structures, slump folds and convolute bedding. Local sills of metagabbro and meta-ultramafics are also seen within the basaltic sequence. The base of the formation is marked by Lakya Quartzite that is locally pebbly and contains herringbone and trough cross bedding (Fig.3D-10c).

*Santaveri Formation*: This formation is also dominated by metabasalts with sills of gabbro, serpentinite and ultramafic schists. Major ultramafic sills are seen in the northwest near Shankaraghatta and Kavalapura. The metabasalt is largely amygdular, but locally contains pillow structures and volcanic breccias. At most places the metabasalt contains carbonate and muscovite and is spilitic. Meta-rhyolites with flow banding, and acid tuffs are seen within metabasalts at Galipuje. At the base of the formation is the prominent cross-bedded fuchsite quartzite, called Kaimara Quartzite in the south and Tanigebail Quartzite in the north.

*Mulaingiri Formation*: This formation begins with chloritic phyllite with sporadic graphitic and phyllitic types ('black shales'). Thin interbeds of quartzite and siltstone are seen locally. The prominent lithology of this formation is the Algoma-type BIF ranging in composition from oxide to silicate facies; significantly, carbonate facies and manganese formations are absent. The BIF contains minnesotaite, stilpnomelane, cummingtonite, grunerite, aegirine and magnesio-riebeckite in some layers. Seams of amosite asbestos (asbestiform grunerite) and crocidolite (asbestiform riebeckite) are seen locally. Some crocidolite seams contain hawk's eye, a semi-precious stone similar to tiger's eye. The asbestos has been explored and found to be uneconomic.

### *Chitradurga Group*

In the Bababudan schist belt, *Mundre Formation* in the northeast, and the homotaxial *Jagar Formation* in the synclinal core of Jagar valley in the west represent the Chitradurga Group. Mundre Formation consists essentially of Kaldurga Conglomerate with associated phyllites, quartzites and local BIF. Jagar Formation, on the other hand, consists of metabasalts, siliceous phyllites, felsic volcanics and pyroclastics. The chert-phyllite association overlying the BIFs of Mulaingiri Formation in the west shows facies change into the quartzite-phyllite association of Mundre Formation towards the east. The Saraswatipura Conglomerate that overlies the basement gneiss in the east underlies the quartzite-phyllite association. BIF occurs as prominent bands within the quartzite-phyllite association. Polymict conglomerate begins to occur between the two BIF bands in the northeast and continues as a major horizon in Kaldurga syncline. The conglomerate (Fig.3D-10d) is graded bedded and shows partial Bouma cycles. Kaldurga Conglomerate contains phyllitic to greywacke matrix in the lower part with clasts of quartzite, BIF and amphibolite. This unit passes into arkosic matrix bearing conglomerate that contains clasts of basement TTG gneisses and granitoids with subordinate quartzites, amphibolites etc. of the Bababudan Group. This difference in clast and matrix composition suggests the stripping of Bababudan cover, which has contributed clasts to the lower part of Kaladurga Conglomerate, followed by the uplift of the gneissic basement that contributed the granitoid clasts and matrix to the upper part of the polymict conglomerate.

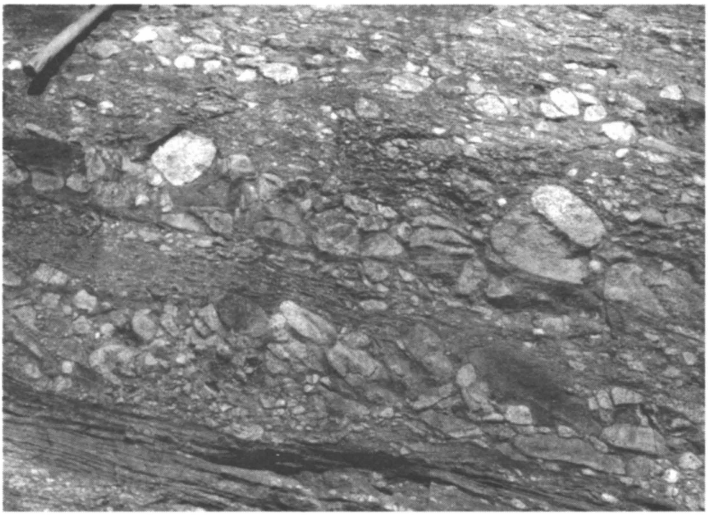


**Fig.3D-10d.** Polymict Kaldurga conglomerate near Shivapura.

### *Sedimentation*

The basal quartz-pebble conglomerate is interpreted as indicative of either braided river or beach face environment. The clast size and current directions indicate deposition from west to east, with a westerly provenance occupied by TTG gneisses. The associated quartzites and minor BIF may indicate near shore to lagoonal environment. The amygdular metabasalts are probably subaerial flows, but local pillows and volcanic breccias indicate eruption under water. The chert-phyllite association and BIF represent a barred basin with restricted clastic output. The lower part of Kaldurga Conglomerate represents debris flows in submarine fans, whereas the upper part suggests bed load processes in an alluvial fan.

Bababudan basin marks great subsidence in the east and northeast. The basin was uplifted in the east and eroded, probably at the initial stage of basin inversion. This is evidenced by the absence of lower Bababudan formations in the area and pouring in of the detritus of Bababudan Group, followed by that of Peninsular Gneiss basement into Kaldurga Conglomerate. Bababudan belt may therefore be a half-graben structure with main faulting in the east. Complex evolution involving faulting in the north, east and west of the basin due to sinistral transpression has analogy with 'mixed mode basins' found in Phanerozoic oblique-slip mobile zones (Chadwick et al. 1989).

### *Structure*

The boundary between Bababudan Group and the basement gneiss with Sargur enclaves is an unconformity that is faulted and steepened by south-verging folds. The boundaries on the west, east and north are marked by steep faults along which the gneisses are mylonitised. Displacements on the faults are related to the uplift of the basement followed by shortening. The dominant folds in the basin are upright open folds with curved hinges. The main fold is the Bababudan syncline that curves westwards. To the east of it is a saddle zone of the N-S trending Santaveri anticline. Some hold the view that regional structure is dominated by synchronous refolding, whereas other workers opine that the early structures trend E-W (Bababudan syncline) and are superposed by N-S trending structures (Santaveri anticline). Recent studies have also shown that the earlier view of large-scale isoclinal structures with the axes along the central arcuate BIF is no longer tenable (Chadwick et al. 1985).

## **Sigegudda Schist Belt**

The small (30 km$^2$) spindle-shaped Sigegudda schist belt near Hassan is a miniature version of Bababudan belt. The schist belt trends roughly N-S with easterly dips and has a faulted eastern contact marked by mylonite. The basal quartz pebble conglomerate-quartzite at the western margin is offset at many places along the strike by transverse faults. The lithological succession overlying the conglomerate is petrologically and geochemically very similar to that of Bababudan belt.

The basal conglomerate truncates the NW banding in the basement gneisses with their concordant Sargur enclaves, along the folded angular unconformity (Fig.3D-11). The Sargur enclaves are mafic-ultramafic schists

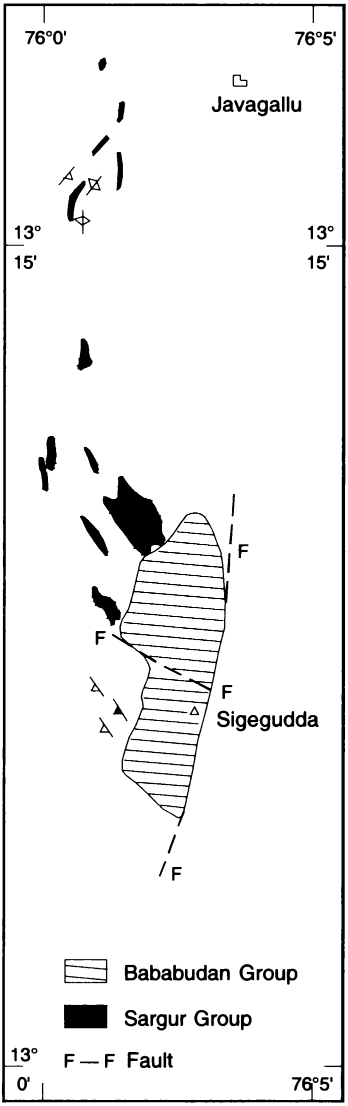


**Fig.3D-11.** Angular unconformity between Peninsular Gneiss with Sargur Group enclaves and Dharwar sequence at Sigegudda (simplified from Viswanatha et al. 1982).

in the north, garnet-biotite schist and BIF further south. The unconformity is disputed by some authors who interpret it as cleavage-bedding intersection in an area where the Dharwar, Sargur and Peninsular Gneiss are believed to have 'unity of structures'. The regional truncation of trends along the angular unconformity is, however, established by the enclave nature of Sargur schists of higher metamorphic grade, their granitic veining and structural concordance with the gneisses, as against the coherent stratigraphy of the low-grade, unmigmatised Bababudan schists that are correlatable on craton scale. The apparent parallelism of fabrics is due to the refraction of cleavage of Dharwar schists in the synformal closure of the Sigegudda belt in the north. This belt is therefore a classical area to establish Sargur-Dharwar-Peninsular Gneiss relationship.

### Western Ghats Belt

This is a large schist belt covering an area of about 2200 $km^2$ and extending from Kuduremukh in the south to Jog Falls in the north through Agumbe and Kodachadri peaks. Further north it passes into Shimoga belt beyond Sharavathi River up to Goa. The belt is approximately 150 km long and 15 km wide on the average. The stratigraphic succession is similar to that of Bababudan schist belt. The basal bed resting unconformably over the basement gneiss is the oligomict quartz-pebble conglomerate (Walkunji Conglomerate) with associated cross-bedded quartzite (7 m thick) extending intermittently along the western margin for about 130 km. The conglomerate is mineralogically and texturally similar to Kartikere Conglomerate of Bababudan belt. This conglomerate was also explored for uranium but the grade and tonnage were found to be marginal. A thick pile of amygdular metabasalts with rare agglomerates, interbeds of quartzites, phyllites and minor BIF overlie the conglomerate-quartzite bed. Thin bands of dolomitic limestone are rare. The metabasalts are geochemically similar to the Bababudan lavas. A prominent horizon of ultramafic schists occurs within basalts, which is similar to that of Santaveri Formation of Bababudan belt. A major unit of Algoma-type BIF caps the Aroli hills of Kuduremukh area, and the Kodachadri hills, where they were explored for iron ore. The iron ores of Kuduremukh were mined for export. The BIF contains rare seams of amosite asbestos and local layers rich in alkali amphibole. The iron formation belongs to oxide and silicate facies, but rarely has carbonate facies also. Geochemistry of iron formation indicates La enrichment, positive Eu anomalies and depleted REE suggesting hydrothermal contribution, whereas enrichment of K, Al, Zr and Rb in shaly BIF suggests continental source. The BIF is overlain by a major horizon of basalts, chloritic phyllites and felsic volcanics and pyroclastics (quartz porphyry, felsite etc.), which are typically exposed in Narasimhaparvatha, and these correspond to the Jagar Formation of Bababudan belt.

### Shimoga Schist Belt

This belt trending NW (Fig.3D-12) covers an area of 25,000 km$^2$ and extends from Tarikere valley to Goa and beyond to Ratnagiri in Maharashtra. It is separated from Bababudan and Western Ghats belts by TTG gneisses but is linked through small arms of schists. The main rock formations of the belt belong to Chitradurga Group, but the Bababudan Group has limited extent and overlies the basement gneissic domes of Londa, Chandragutti, Kumbharwada, Shimoga, Honnali, Saulanga and the cluster of domes between Tarikere and Chennagiri. Basement-cover unconformities are seen at many places. Locally, the schists at the gneissic contact are marked by higher metamorphic grades with garnet developing in amphibolites as at Dummi, and kyanite forming in mica schists at Joga, Kalavarangan Durga and Chennagiri. Further, quartzo-felspathic veins are locally seen in the schists at some contacts due to incipient remobilisation of the gneiss (i.e., low grade partial melting) coincident with deformation in shear zones, and medium grade metamorphism. Younger intrusive granitoids are, however, found in the schist belt mainly in the northern part.

#### *Sargur Group*

Small lenses of serpentinite (e.g., at Amrutapura) with chrysotile asbestos and chromite, as well as other ultramafic schists, amphibolites and BIF belonging to Sargur Group are seen to the north of Tarikere valley, where they occur close to the basement-cover unconformity. Enclaves in the northern extensions of Nuggihalli and JCPura belts (e.g. Antaraghatta belt) also underlie the Dharwar rocks of Shimoga schist belt.

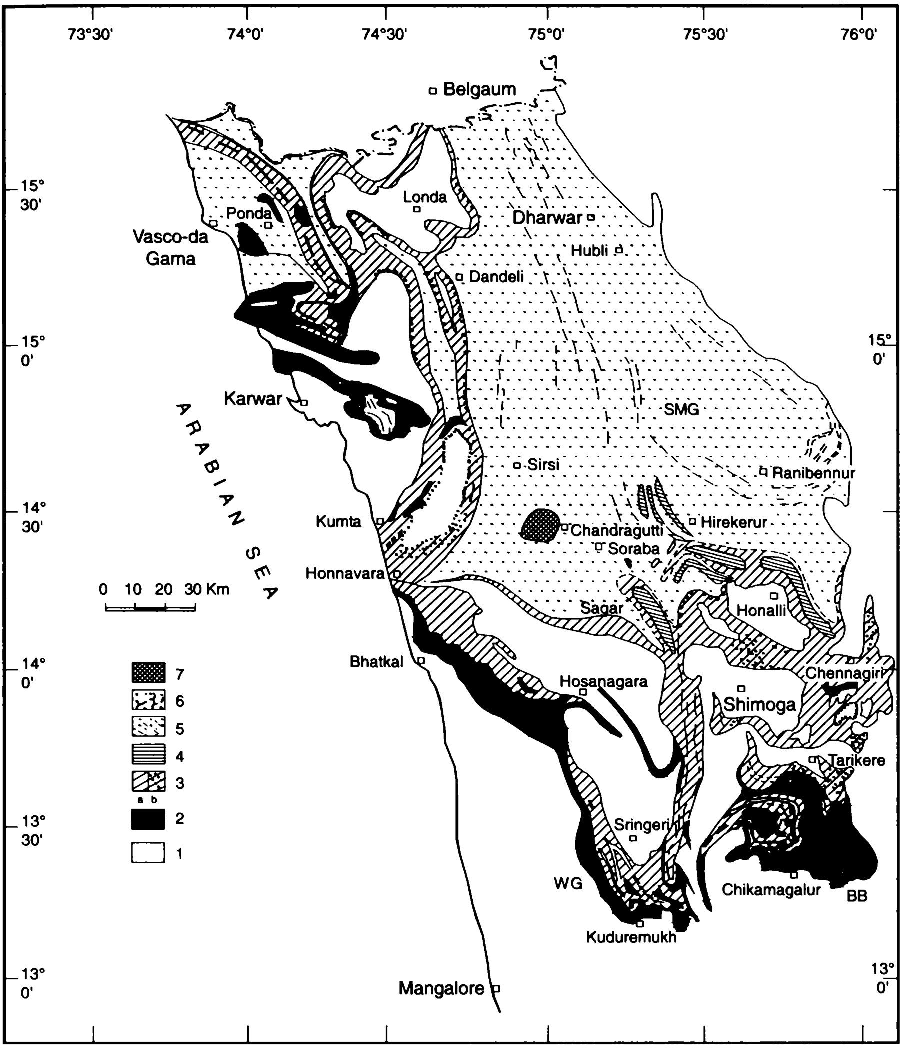
#### *Bababudan Group*

In the western part of Shimoga belt, Bababudan Group occurs prominently around Karwar and Kumbharwada and rather sparsely around basement gneissic domes in the south. Bababudan Group consists essentially of dark green metabasites rich in secondary carbonates and amygdales of quartz, carbonate and chlorite. Locally the metabasalt is pillowed. Sheets of differentiated sills of basic-ultrabasic rocks contain lenses of chromite and bands of titanomagnetite. The sills at places host sulphide mineralisation. Important layered sills are found near Madanjeri, Kaiga, Durgagudda, Kumbharwada and Usgaon. The metabasalts are interbedded with cross-bedded quartzites and phyllites and rarely overlie pebbly quartzite resting over basement granites in Goa and at Duruvigere and Nallur. Minor felsic volcanics and tuffs are also seen. Bababudan Group of this belt is correlated with the Santaveri Formation of Bababudan belt on the basis of lithological similarity, especially the presence of pillowed basalts and basic-ultrabasic sills. Bababudan Group passes upward into the lower part of Chitradurga Group through an ensemble of quartzites, phyllites and polymict conglomerates, which are the equivalents of Kaldurga Conglomerate and associated sediments of Mundre Formation.

### *Chitradurga Group*

This group in the Shimoga belt shows enormous lithologic variations within short distances due to frequent facies changes and lateral impersistence of formations. Apart from these sedimentalogical handicaps, there are numerous closely placed basement domes within and marginal to the schist belt, which compound the problem of stratigraphic correlation. Recently B. Chadwick and his co-workers have carried out controlled reconnaissance mapping on 1:50,000 scale in the southern part of the schist belt near Bhadravathi and Honnali (Chadwick, 1994). They divided the lower part of the Chitradurga Group into eight formations consisting of an ensemble of polymict conglomerates, phyllites, greywackes, orthoquartzites, limestone, dolomite and sporadic BIF bands. Metabasic intercalations are common. The greywacke and BIF are locally rich in manganese oxide resulting in mining of manganese ores on a large scale. The limestones are used in the cement industry. At the top of this lower unit, a major basic to acid volcanic complex is seen in Daginkatte-Malebennur area.

Polymict conglomerates occur at many levels and some were deposited on the basement. They vary from lenses to large complexes and are mostly unsorted. Matrix is greywacke or arkosic in composition. Clast compositions in the order of abundance upward in the stratigraphy are metabasite, cross-bedded arenite with phyllite and gneiss/granite. These appear to have been deposited on progressively subsiding depressions between basement domes during the initial basin inversion, and this indicates the stripping of Bababudan cover first, followed by denudation of the basement gneiss and granodiorite. Composite units of conglomerate-orthoquartzite are comparable to shallow alluvial or marine fans. Coarse pebbles and large clasts represent storm surge and debris flow deposits, whereas the fine conglomerates are probably sheet flood deposits. Herringbone cross bedding indicates intertidal to near shore facies. There were intermittent suggestions that the


73°30'
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Dharwar
Hubli
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Ponda
Vasco-da Gama
Karwar
ARABIAN SEA
SMG
Sirsi
Ranibennur
Kumta
Chandragutti
Hirekerur
Soraba
Honnavara
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**Fig.3D-12.** Geological map of Bababudan-Western Ghats-Shimoga superbelt (from Radhakrishna and Vaidyanadhan, 1997). (Schist belts: BB-Bababudan, WG - Western Ghats, SMG - Shimoga). 1- Peninsular Gneiss, 2 - Bababudan Group, 3 - (a) Vanivilas Subgroup; (b) - Polymict conglomerate, 4 - Felsic volcanics and 5 - Greywacke with BIF of Ranibennur Subgroup, 6 - Manganese horizon, 7 - Granite.

conglomerates may be glacial or fluvioglacial in origin, but substantial proof is yet to come.

Impersistent orthoquartzite is found in the phyllite-arenite sequence. Trough and herringbone cross bedding, and wave and current ripple bed forms in arenites indicate shallow marine conditions. Some phyllitic greywackes preserve soft sediment deformation structures. Greyish calcitic to dolomitic limestone occur as thin interbeds in greywackes. Fine-grained carbonate-chert unit containing stromatolitic structures support the idea of shallow marine conditions. Sedimentary breccia hosted by limestone indicates the presence of local debris flows.

A major belt of volcanic rocks with local greywacke, BIF and limestone occurring near Malebennur forms the topmost formation of Vanivilas Subgroup. The volcanic complex consists of two major units viz., a metabasalt-basaltic andesite association (Medur Formation) and an acid volcanic association (Daginkatte Formation). The metabasalt-basaltic andesite unit is pillowed with local volcanic breccia. The felsic unit is regarded as either a flow-banded rhyolite or rhyolitic ash flow tuff of probable subaerial origin. The rhyolite is enriched in $K_2O$ (7.7%). The felsic volcanics are dated by Rb-Sr, Pb-Pb and SHRIMP U-Pb methods at about ~2600 Ma, which sets the upper limit of Dharwar orogeny.

The upper part of Chitradurga Group (Ranibennur Subgroup) begins with a persistent but thin (50 m wide) unit of BIF, associated with carbonaceous phyllites. Ranibennur Subgroup denotes a radical change from the unstable shelf of Vanivilas Subgroup to shallow lagoon or deep offshore muds. The BIF-phyllite unit is overlain by a vast expanse of fine-grained greywacke, associated frequently with BIF, felsic-mafic volcanics and adakites (Naqvi and Rana Prathap, 2007). The greywacke varies in composition from quartz wacke to lithic wacke and contains flute casts, sole marks etc. The greywacke may represent offshore distal turbidite or indicate marine accumulation from a provenance of low relief.

### *Structure*

The structure of the Shimoga belt (Fig.3D-13) is characterised by southwest verging folds in Dharwar schists and by north dipping reverse faults forming the southern boundaries of basement domes like Tarikere, Honnali and Shimoga. The northern boundaries of these domes are unconformities steepened by folding. The cover rocks are deformed in a ductile manner with local decollements (e.g., Nidnegal anticline) and form upright folds between basement domes that are separated by shear zones. Horizontal sinistral displacement is noticed in some shear zones. The basement gneisses, on the other hand, are deformed in myriad brittle fractures as well as ductile, mylonitic shear zones. The major shear zone at the eastern margin of the belt, extending from Bababudan belt, has numerous BIF bands within greywackes swerving into it near Harappanahalli. Abundant carbonates seen in fractures attest to the role of $CO_2$ activity. These events denote two periods of deformation. The evolution of Shimoga belt is governed by sinistral transpression in an ensialic oblique-slip mobile zone (Chadwick, 1994).

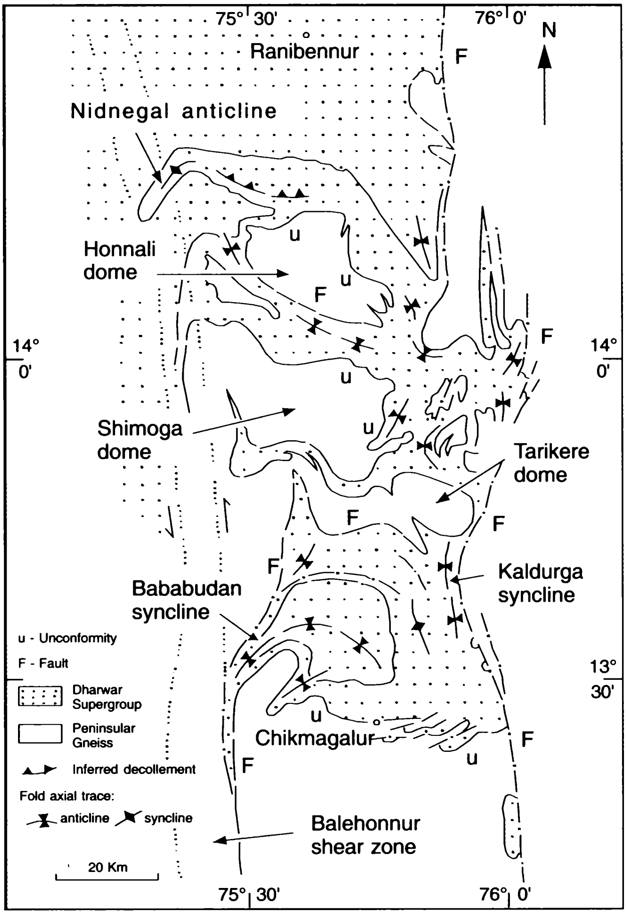
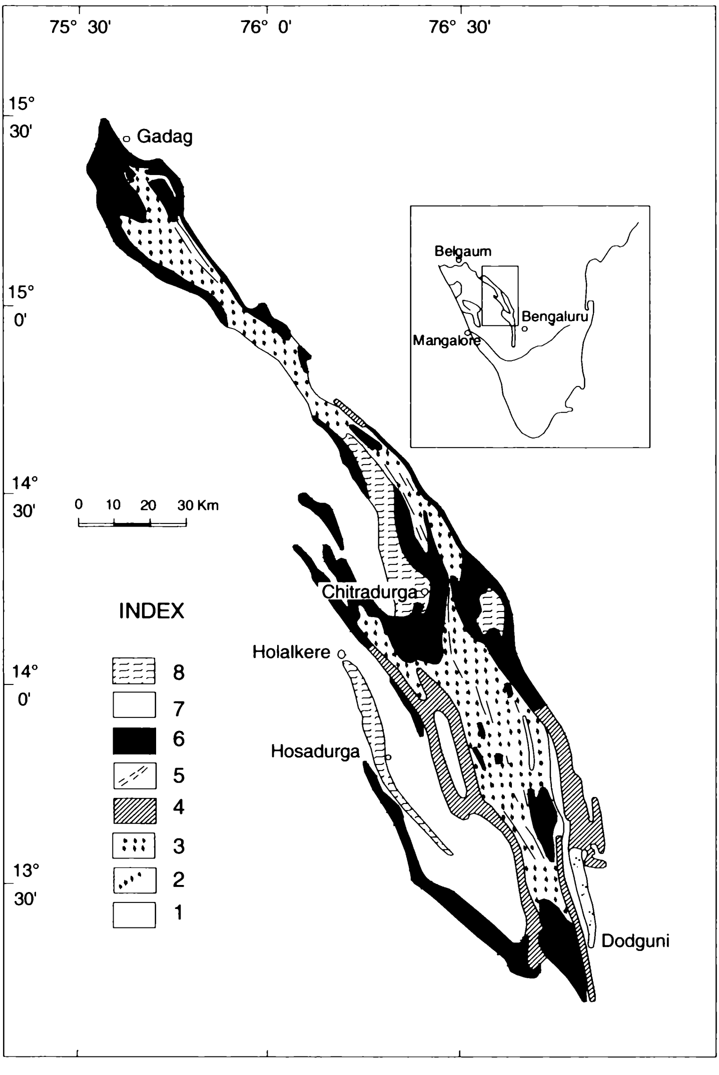

75° 30'
76° 0'
N
Ranibennur
F
Nidnegal anticline
Honnali dome
u
F
14° 0'
Shimoga dome
Tarikere dome
F
Bababudan syncline
Kaldurga syncline
13° 30'
u - Unconformity
F - Fault
Dharwar Supergroup
Peninsular Gneiss
Inferred decollement
Fold axial trace:
anticline
syncline
20 Km
Chikmagalur
Balehonnur shear zone
75° 30'
76° 0'

**Fig.3D-13.** Structures in a part of Shimoga belt (after Chadwick, 1994).

### Chitradurga-Gadag Superbelt

This long linear superbelt (Fig.3D-14), known commonly as Chitradurga schist belt, is about 400 km long and 40 km wide in the middle. It tapers to about 5 km width in the north with wide bulges of about 25 km near Gadag and Dodguni. Although contiguous with the main Chitradurga belt, the Gadag part is described sometimes as Gadag schist belt because of its significance for gold. The schist belt covers an area of about 6000 km$^2$ and exposes the complete succession of cratonic rocks viz., Sargur and Dharwar supracrustals, basement and intrusive gneisses and younger K-rich granitoids. Sargur Group is well represented in this belt by the Ghatti Hosahalli, J.C.Pura and Mayasandra bands. The Bababudan Group occurs to a limited extent and is marked by the orthoquartzite-metabasalt association in Kibbanahalli-Dodguni, Mayakonda (near Holalkere), Brahmasagara, Honakere, Chitradurga-Gadag, Hagalvadi (Javanahalli), and Yadiyur-Karighatta areas.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Gadag
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Mangalore
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INDEX
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4
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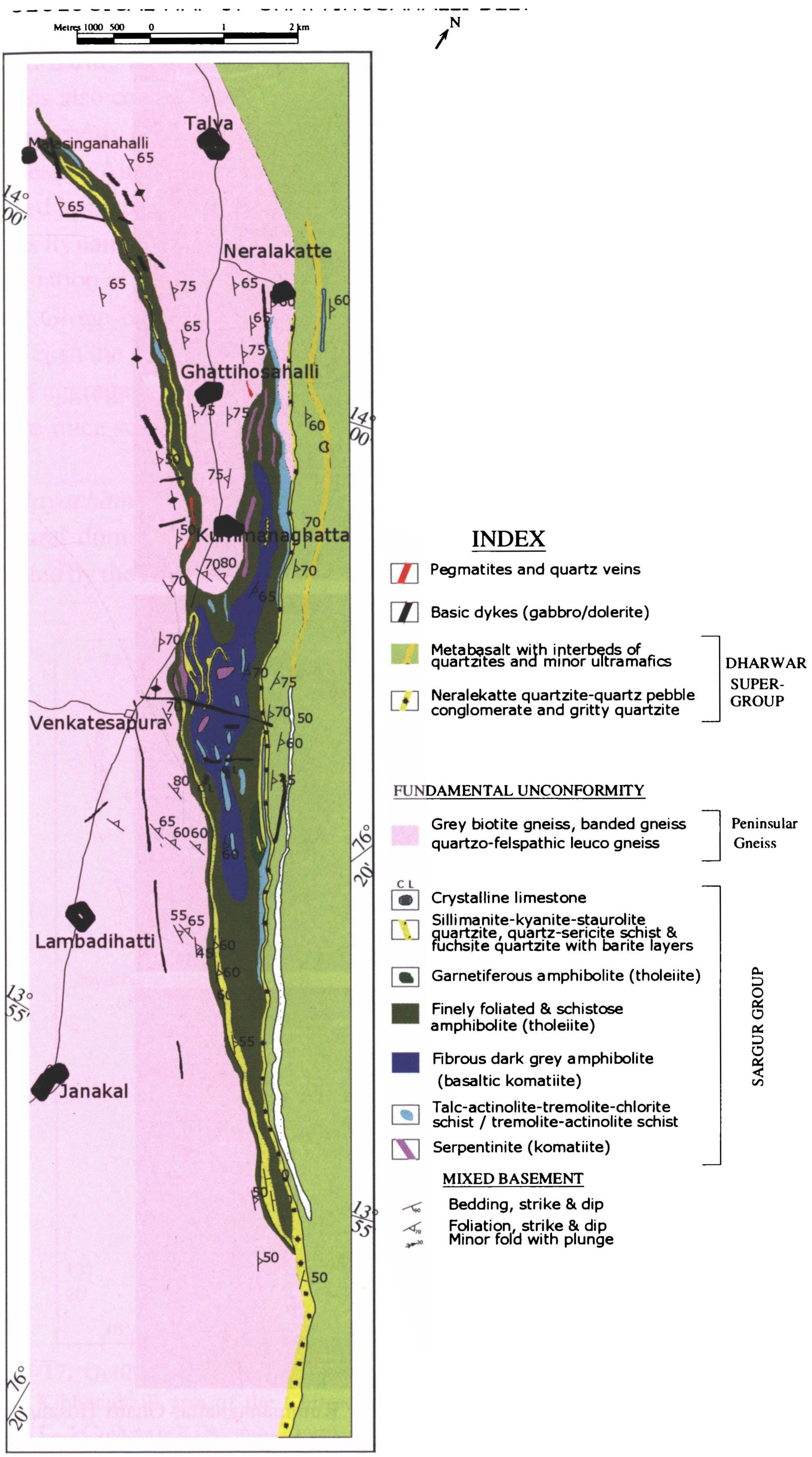
2
1
Chitradurga
Holalkere
Hosadurga
Dodguni

**Fig.3D-14.** Geological map of Chitradurga-Gadag superbelt. **1** - Peninsular Gneiss; **2** - Conglomerate; **3** - Quartzite; **4** - Phyllite with iron-manganese marker horizon; **5** - Banded Iron Formation; **6** - Mafic flows; **7** - Greywacke; **8** - Intrusive granite. Mafic flows of Bababudan and Chitradurga Groups are not differentiated in the map (after Radhakrishna and Vaidyanadhan, 1997).

### *Sargur Group*

*Ghatti Hosahalli Belt* (Fig.3D-15)*:* It is a linear string of enclaves best exposed near Ghatti Hosahalli and Holalkere. The importance of this belt lies in its proximity to the Dharwar unconformity at Neralekatte and Kummanaghatta where the basal conglomerate-quartzite is well exposed. The geological section from Ghatti Hosahalli to Talya ideally demonstrates the Sargur-Peninsular Gneiss-Dharwar relationship. The hillocks and mounds near Ghatti Hosahalli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Talya
Neralakatte
Ghattihosahalli
Kummanaghatta
Venkatesapura
Lambadihatti
Janakal
14° 00'
13° 55'
76° 20'
INDEX
Pegmatites and quartz veins
Basic dykes (gabbro/dolerite)
Metabasalt with interbeds of quartzites and minor ultramafics
Neralekatte quartzite-quartz pebble conglomerate and gritty quartzite
DHARWAR SUPER-GROUP
FUNDAMENTAL UNCONFORMITY
Grey biotite gneiss, banded gneiss quartzo-felspathic leuco gneiss
Peninsular Gneiss
CL
Crystalline limestone
Sillimanite-kyanite-staurolite quartzite, quartz-sericite schist & fuchsite quartzite with barite layers
Garnetiferous amphibolite (tholeiite)
Finely foliated & schistose amphibolite (tholeiite)
Fibrous dark grey amphibolite (basaltic komatiite)
Talc-actinolite-tremolite-chlorite schist / tremolite-actinolite schist
Serpentinite (komatiite)
SARGUR GROUP
MIXED BASEMENT
Bedding, strike & dip
Foliation, strike & dip
Minor fold with plunge

**Fig.3D-15.** Geological map of Ghatti Hosahalli belt (after Paranthaman, 2005).

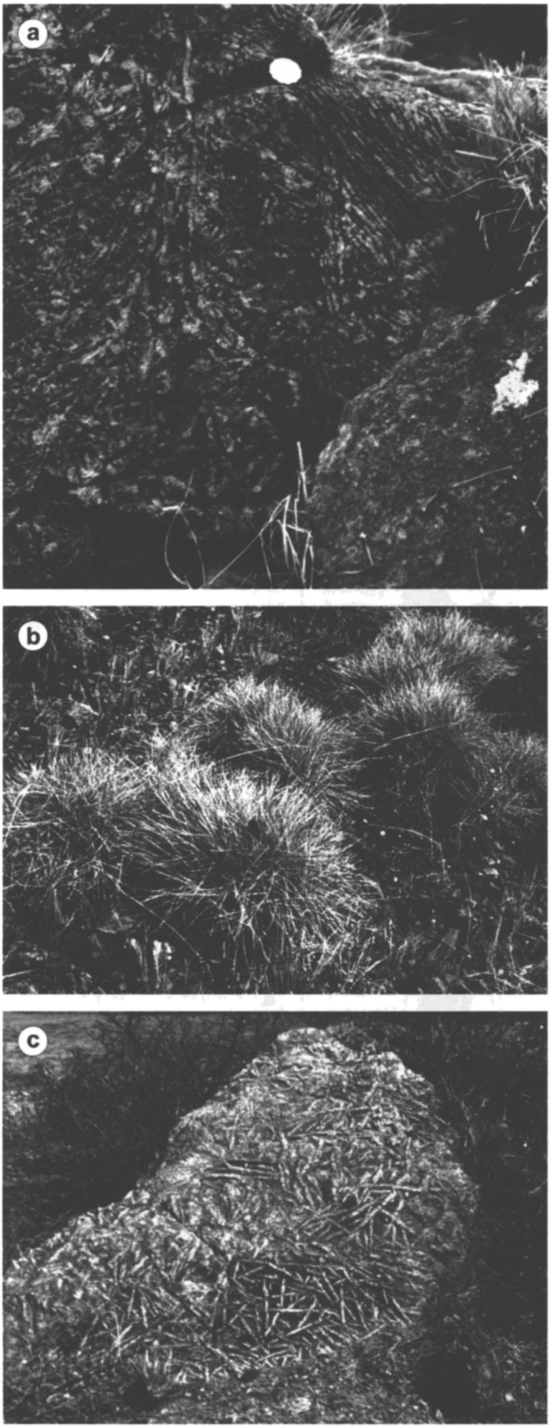


**Fig.3D-16. (a)** Spinifex textured serpentinite near Kummanaghatta, Ghatti Hosahalli belt (Courtesy: M.N. Viswanatha). **(b)** Spinifex grass in Australia from which the term spinifex texture is derived. **(c)** Bladed aggregates of kyanite in mica schist at Kudinirkatte near Holalkere.

are made of fuchsite-kyanite±staurolite quartzite closely interbanded with bedded barite, an unusual association not seen in the Dharwar. The quartzite contains also celsian and uvarovite. The barite-fuchsite quartzite association is of sedimentary origin, as seen elsewhere in the greenstone belts of South Africa and Western Australia. Another important rock type (Fig.3D-16a) is the spinifex-textured komatiites (serpentinites and ultramafic schists). The spinifex texture derives its name from the spinifex grass of Australia (Fig.3D-16b). Such unusual combination of komatiites and arenites is also known from the Archaean Prince Albert Group of Canada (Schau, 1977). Ultramafic schists are widespread as enclaves in the gneissic plains. Near Holalkere, kyanite-mica schists with large, bladed aggregates of kyanite are exposed in a large enclave (Fig.3D-16c). The kyanite-mica schist yields Sm-Nd (TDM) model age of 3100 Ma.

*Jayachamarajpura (J.C.Pura) or Halakur belt:* A major N-S trending structural dome, rimmed by ultramafic-mafic rocks and cored by gneiss, is truncated by the Dharwar unconformity of Kibbanahalli arm (Fig.3D-17). Linear

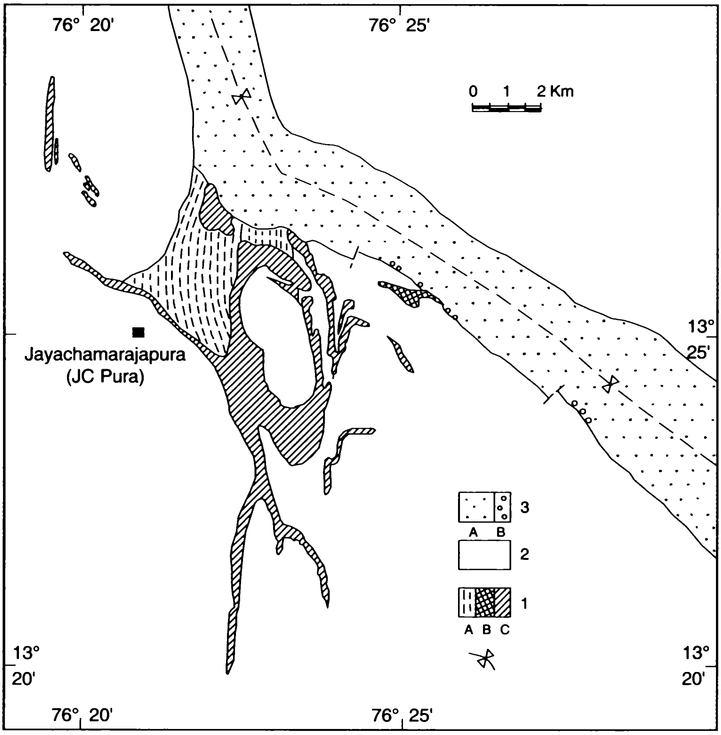


**Fig.3D-17.** Geology of J.C. Pura schist belt showing angular unconformity with the Kibbanahalli arm of the Chitradurga schist belt (after Venkata Dasu et al. 1991). **1** - J.C. Pura belt (Sargur Group), **A** - Schistose amphibolite, **B** - Dark grey amphibolite; **C** - Ultramafics including komatiite, **2** - Peninsular Gneiss; **3** - Kibbanahalli arm A:Bababudan Group; B: Basal Conglomerate.

enclaves of this belt, called the Antharaghatta schist belt, extend to the north of the dome up to Kallangavi. J.C.Pura belt is well known for its spinifex textured komatiites (Fig.3D-18a) that also exhibit pillows (Fig.3D-18b), ocelli and polyhedral joints. Rarely, fine-grained quartzite is seen in the belt. These detrital quartzites give SHRIMP U-Pb age of ~3300 Ma, which is also corroborated by the Sm-Nd dating of the ultramafics.

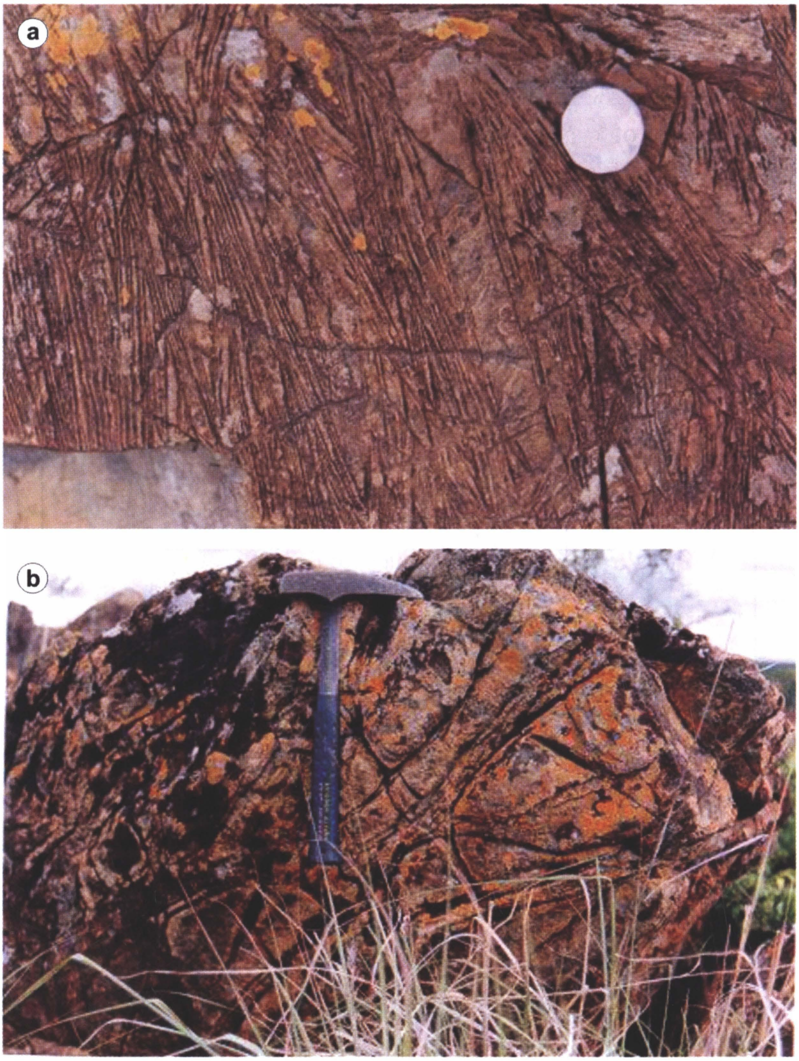


**Fig.3D-18.** (**a**) Spinifex textured komatiite at J.C. Pura. (**b**) Pillowed komatiite, J.C. Pura (Courtesy: M. Jayananda).

*Mayasandra Belt*: A linear band of amphibolites and spinifex-textured ultramafics underlies the Dharwar basal quartzite at Dandinashivara, close to Dodguni.

### *Bababudan Group*

*Kibbabahalli Arm:* A synclinal arm wrapping around the Chikkanayakanahalli (CNK Halli) gneissic oval joins the main Chitradurga belt near Dodguni. The basal conglomerate in the belt is overlain by metabasalt-quartzite succession with minor BIF. Locally, agglomerates and volcanic breccias are seen in metabasalts. Kibbanahalli arm was interpreted as a decollement earlier, but it appears to be a synclinal keel that unconformably overlies the basement gneisses containing Sargur enclaves.

*Mayakonda band:* Quartzite-metabasalt alternations that overlie the basal conglomerate are well exposed from Mayakonda to Vanivilasa Sagara at the western margin of Chitradurga belt. Near Mayakonda, the sequence overlies the Kandavadi basement dome. Polymict conglomerate is exposed within the gneiss along a faulted strip. Typical Bababudan succession is also exposed in the *Brahmasagara (Halekal) outlier* in the northeast of Mayakonda.

*Honakere Arm:* A linear arm consisting of amphibolite, quartzite and BIF of Bababudan Group branches off from the main Chitradurga belt near Honakere. On the periphery of the arm, concordant bands of ultramafic rocks of Sargur Group are seen adjacent to the gneisses.

*Yadiyur-Kạrighatta Arm*: Chitradurga belt narrows down south of Dodguni and consists of typical amphibolite-quartzite-pelite association with some BIF. As the belt constricts, it splits into narrow tongues around gneissic domes as at Honakere and Waruna. Higher metamorphic grade evidenced by kyanite-staurolite-mica schists in the belt suggests similarity to Sargur Group, as in the case of Tattekere Conglomerate of Hole Narasipura belt, but the strike continuity of the Bababudan rocks in both the belts confirms its correlation with the Dharwar sequence. Sargur ultramafics (locally with spinifex texture) occur at the margins of the belt in Honakere and Karighatta areas.

### *Chitradurga Group*

*Chitradurga Arc to Dodguni:* Chitradurga Group covers most of the belt, and starts with the polymict Talya Conglomerate associated with siliceous schists (quartz-sericite-chlorite schists) that mark the transitional contact with Bababudan Group. Talya Conglomerate, like the Kaldurga Conglomerate of Shimoga belt, consists of clasts of basement gneiss and granitoids, and of the Bababudan Group, especially the resistant orthoquartzites. Bababudan Group was deformed, uplifted and eroded together with the basement, before Chitradurga Group was deposited.

Two major lithologic packages constitute Chitradurga Group, the lower Vanivilas Subgroup and the upper Ranibennur Subgroup. Vanivilas Subgroup consists of quartz arenite, phyllite, limestone/dolomite, manganese formations and BIF. The arenites are cross-bedded and ripple marked. The 'gritty' phyllites are locally used as grinding stones. Limestones are stromatolite bearing and support small cement plants. Locally, the carbonates are brownish-weathering dolomites. Manganese is worked as concentrations in carbonates, phyllites, cherts and BIF. The manganiferous cherts show negative Ce anomaly. The Pb-Pb ages of carbonates and Rb-Sr ages of cherts correspond to the age of regional metamorphism at ~2600 Ma. BIF occurs in three bands, the lower band being of limited extent and separates the Jogimaradi and Ingladhal volcanics. Jogimaradi volcanics may correlate with the Bababudan Group of the western margin of the schist belt. Ingladhal volcanics may correspond to the Vanivilas Subgroup at the western basin margin. The middle BIF band is a prominent marker horizon that contains also manganese. The upper BIF band (Fig.3D-18c) occupies the flanks of the belt and forms the top of Vanivilas Subgroup. The oxidised BIFs are locally mined as iron ore.

The lithologic association of arenite, pelite, carbonate, chert, manganese formation and BIF (oxide and carbonate facies) occurring at the continental margin in the west (Vanivilas Subgroup), passes laterally into metavolcanics (Ingladhal Volcanics) extruded on gneissic basement, and BIF (manganiferous

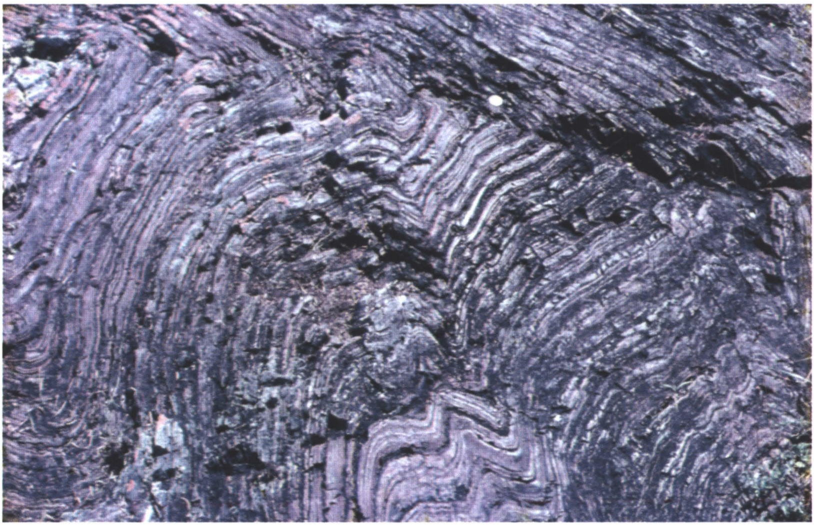


**Fig.3D-18c**. The third BIF band near Elkuranahalli.

and sulphidic facies) at the deeper part of the basin in the Chitradurga anticline denoting a significant facies change. The metavolcanics are extensively pillowed (Fig.3D-18d) and show variolitic and agglomeratic structures. Fine-grained phyllites associated with the volcanics may be tuffs or tuffaceous sediments. Local volcanic centres with abundant felsic volcanics and volcanoclastics of dacitic to rhyolitic composition are seen at Tekalvatti and Aimangala. The basic volcanics and sulphidic cherts host deposits of copper and gold (as at Ingaldhal), with minor lead and antimony. The volcanics and BIF are well developed in Chitradurga anticline, Maradihalli, Bellara and Gadag.

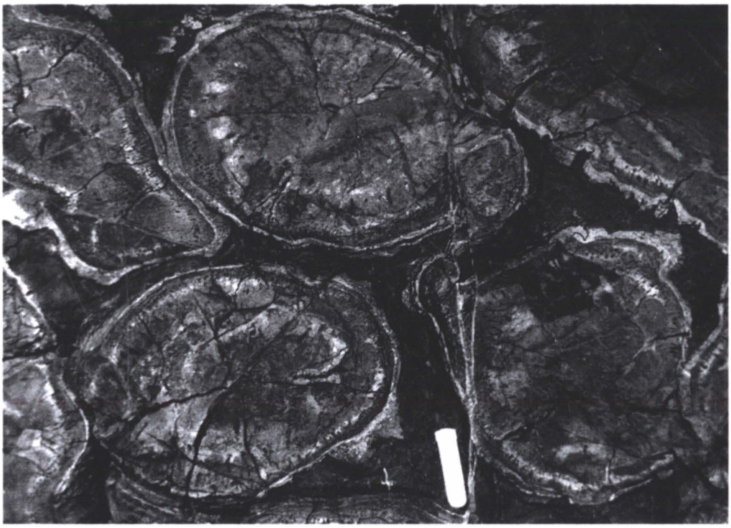


**Fig.3D-18d.** Pillow lava at Maradihalli. Thin rind, vesicle zone and radial cracks are characteristic.

Compositionally, the basic volcanics are essentially tholeiitic metabasalts and basaltic andesites. True andesites are rare. These metavolcanics are enriched in transition elements, suggestive of shallow melting of a mantle source and are not significantly fractionated. Geochemical discriminant diagrams of metabasalts indicate a marginal basin environment. Rb-Sr isotopes in the volcanics appear to have been disturbed, as seen in their younger ages of 2200–2300 Ma, but Sm-Nd ages are ~2750 Ma, probably corresponding to the age of eruption.

Vanivilas Subgroup is conformably overlain by the Ranibennur Subgroup consisting of fine-grained greywackes at the basin margin as well as in the deeper parts of the basin. These greywackes are distal turbidites that are interspersed with mafic-felsic volcanics and volcanoclastics, BIF, rare carbonates, and polymict conglomerate horizons. The greywackes alternate with fine-grained phyllites that form the greywacke-argillite suite of orogenic belts. The lithic fragments in greywackes suggest their derivation from a dominant source of TTG gneisses (Peninsular Gneiss) with subordinate mafic to ultramafic rocks (Bababudan Group). Volcanic debris in the greywacke indicates contemporary volcanic source. Their high Cr, Ni, and Zr content, LREE enrichment and negative Eu anomalies corroborate this conclusion.

*Chitradurga Arc to Gadag:* In the arcuate region around Chitradurga, Bababudan Group is represented by Jogimaradi metabasalt ('Jogimaradi Trap') that consists of pillowed, variolitic, agglomeratic, and tuffaceous metabasalt overlain by a prominent BIF band, together suggesting a deep-water setting. The same BIF horizon overlies the shallow water sequence of Talya conglomerate-metabasalt-quartzite at the western margin of the belt, which means that the shallow and deep-water sequences are facies variants of one another, and are homotaxial. This geological setting, when extended further north, shows that the metabasalts and BIF exposed along the western margin of the schist belt from Chitradurga to Gadag may belong to Bababudan Group.

### *Sedimentation*

Talya polymict conglomerate marks the transition from Bababudan to Chitradurga Groups through a horizon of siliceous schists. The conglomerate represents a debris flow like the Kaldurga Conglomerate of Bababudan schist belt. The conglomerate is succeeded by a shallow marine sequence of quartzite-pelite-stromatolitic carbonate-manganese formations (chert, phyllite and carbonate) and BIF. The shallow-water sequence graduates along strike into the deep-water sequence of mafic volcanics, cherts and BIF that probably represents an offshore deposit. The prominent BIF marker horizon bridges the homotaxial facies variation from shallow shelf to offshore. A thick pile of greywacke turbidites overlies both the shallow-water and deep-water sequences in the centre of the basin. The greywacke-phyllite suite is frequently interbedded with BIF, volcanics, pyroclastics and polymict conglomerates (KM Kere, Aimangala, Yelladakere), and probably represents an offshore deposit.

### *Structure*

Chitradurga belt displays a series of variably plunging synclines and anticlines with steep axial planes trending NNW. The major structure is Chitradurga anticline, which is an upright fold with an undulating axis and near vertical plunge. The anticline is flanked on either side by synclines, and has been interpreted either as second-generation fold or as a penecontemporaneous refold formed during a single progressive deformation. Other prominent folds are Sirankatte, Kandavadi and Dodguni anticlines, and Hiriyur, Kibbanahalli and Yadiyur-Karighatta synclines.

The northern part of the Chitradurga belt near Gadag has been recently studied in detail on account of prominent gold mineralisation. Gadag band has been recently re-interpreted as a structural duplex with numerous tectonic slices characterized by top-to-southwest movement (Chadwick et al. 2003).

Basement-cored domes like Sirankatte and anticlines like Kandavadi and Madadkere are other important features. The status of these basement domes and anticlines has been controversial. The structurally better studied Sirankatte dome was visualised by some authors as a mantle gneiss dome of the type described by Eskola. The basement gneiss of the dome and the rim unconformity have concordant foliation brought about by deformation in lower amphibolite facies, which has also caused sporadic injection of quartzofelspathic veins near the interface. The gneiss is therefore a recognisable basement inlier, unlike the thermally mantled gneiss domes that are usually affected by higher grade of metamorphism and concomitant "reactivation", thereby obliterating its basement nature and resetting the isotopic clocks.

A major sinistral shear zone marks the eastern margin in the north of the schist belt near Gadag. In the middle portion, the shear zone cuts through the eastern edge of the belt, separating the Javanahalli belt from the main Chitradurga belt. In the south, the shear zone passes through the gneiss in the west of Kunigal belt, up to the southern boundary of the craton adjacent to the Biligiri Rangan Hills (BR Hills). The ductile shear zone is marked by mylonitic gneisses near Javanahalli and by the spectacular flinty, layered mylonites of Markonahalli near Kunigal. This prominent shear zone marks the transitional boundary between the WDC and EDC.

## Charnockites

Charnockites displaying spectacular transformation from the TTG suite of Peninsular Gneiss are seen all along amphibolite-granulite facies boundary from Mangalore and Coorg in the west to Nanjangud and Chamarajanagar in the east in WDC. The unbroken transition from arrested charnockites to charnockite massifs is best seen in Coorg and BR Hills. The charnockite massifs are essentially enderbites, with felsic charnockites being important in Chennai. They are compositionally akin to high Ba-Sr granitoids. Basic granulite dykes with clouded plagioclase that marks the transition to granulite facies are also best developed in Coorg. These dykes preserve chilled margins and cross-cutting relation with the host gneisses. Charnockites with associated Peninsular Gneiss continue up to Moyar-Bhavani and Bavali shear zones in the south. Charnockite-gneiss relations, progressive metamorphism and tectono-stratigraphic significance are discussed in later sections.

## Younger Granites in WDC

Late to post-tectonic Dharwar granites (~2600 Ma) that denote crustal reworking in WDC (Jayananda et al. 2006), occur as isolated discrete intrusions cutting across the foliation and banding of Peninsular Gneiss (~3000 Ma), like those of Arsikere, Banavara, Hosadurga and Dudhsagar. Some of them intrude the schist belt also, like the Chitradurga and Jampalnaikankote (J.N.Kote) Granites.

**Chitradurga Granite:** This is an elongate lenticular body of late to post-tectonic granite about 60 km long and a maximum of 15 km wide exposed near Chitradurga town. The granite is clearly intrusive into the Jogimaradi lavas of Bababudan Group as well as the basement gneiss. It is essentially biotite granite grading into granodiorite and quartz monzonite. The more evolved variety of the granite is a potassic type. Recent studies by Chadwick et al. (2003, 2007) have shown that the granite splits into two arms near Brahmasagara (Halekal) outlier and has probably been emplaced as a sheet. The granite has yielded well-fitted Pb-Pb and Rb-Sr isochrons of ~2600 Ma and SIMS U-Pb zircon age of ~2610 Ma. Sm-Nd model age (TDM) of the granite at ~3000 Ma suggests the involvement of the gneissic basement in its genesis.

**Jampalnaikankote (J.N.Kote) Granite:** An oval body of granite intruding the Chitradurga schist belt at the eastern margin near J.N.Kote is clearly seen in the satellite imagery. It appears to be a zoned pluton having a reconnoitary Rb-Sr model age of ~2600 Ma. Similar minor granites are seen further north.

**Arsikere and Banavara Granites:** Arsikere Granite is an oval body of 75 km$^2$ area that occupies a steep hill rising from the gneissic plains near Arsikere. It is potassic biotite granite having two variants of pink and red colour. Rb-Sr isochron gives an age of ~2600 Ma and SIMS U-Pb zircon age of ~2615 Ma. Banavara Granite is similar to Arsikere Granite and forms a cluster of separate hillocks. It is believed that the two granite bodies form part of a large pluton that is connected at depth.

**Hosadurga Granite**: The curvilinear Hosadurga Granite, occupying the hills between the Kibbanahalli arm and the Chitradurga belt, intrudes the basement of C.N.K. Halli gneissic oval and has the trend parallel to the schist belts.

**Chamundi Granite:** A small oval-shaped pluton of potassic granite occurs in the Chamundi Hill in Mysore city. The granite intrudes Peninsular Gneiss and sends out several radial and parallel dykes of felsite, granophyre and felsic porphyry as seen around Srirangapatna. The Rb-Sr age of the granite is ~800 Ma that corresponds to widespread alkaline intrusions in the Dharmapuri rift of EDC and in PMB.

**Alkali Granites and Syenites:** A granitic body similar to Chamundi granite in WDC is the Angadimogar alkali granite of A-type that was described earlier as a syenite. Syenite at Sulliya and alkali granite at Thaluru and Mercara occur in the vicinity of the cratonic boundary in WDC. Numerous bodies of alkaline granites and syenites with associated carbonatite and lamprophyre are reported from the nearby PMB in Tamil Nadu and Kerala. These are described under the section on PMB.

### Other Intrusions in WDC

**Thagaduru (Konkanahundi) layered basic intrusion:** An undated, oval-shaped basic intrusion (50 $km^2$) was picked up by aeromagnetic surveys in the Nanjangud plains (Fig.3D-25), where a lone exposure of norite was seen near Kallukunda. The intrusion is mainly a layered gabbro with cumulates of norite and anorthosite, emplaced into Peninsular Gneiss close to the granulite facies transition zone. The intrusion maybe ~2500 Ma old.

**Kunduru Betta ring intrusion:** (Fig.3D-25) An undated (Dharwar/Pan African?), oval-shaped, N-S trending intrusion consisting of annular rings of mafic syenite rim, porphyritic and quartz syenite in the middle and a core of granite intrudes Peninsular Gneiss near Malavalli near the granulite facies transition zone.

## EASTERN DHARWAR CRATON

The contact between WDC and EDC is not sharply defined, although the Chitradurga Boundary Fault is taken as a convenient and conspicuous marker. Chadwick et al. (2007) define the contact zone as one of diffuse transition that finds some geophysical support (Ramadass et al. 2006). The diffuse zone may be about 200 km wide, probably starting from the northeast sheared margin of Shimoga belt, through the Gadag belt up to the Closepet Granite. The gneisses of the diffuse zone have transitional character in that they have TTG composition like those of the WDC, but are mainly 2500-2700 Ma old like those of EDC. Granites in the west of Gadag belt have ages of ~2600 Ma, with a Pan-African overprint of 500-800 Ma, similar to some granitoids around Sandur belt. The gneisses are also characterised by flat-dipping foliation and banding in the area between Chitradurga shear zone and Closepet Granite. It is not clear whether the flat-lying character is due to sub-horizontal compression or due to thermal doming.

### Transition Zone

The gneisses of the transition zone between the Chitradurga Boundary Fault and Closepet Granite contain schist bands and enclaves forming parts of Chitradurga schist belt that are dismembered, the prominent ones being Javanahalli and Kunigal (Huliyurdurga) belts. The stratigraphy of these belts is comparable to the Vanivilas Subgroup of Chitradurga belt.

**Javanahalli Band:** The schists are juxtaposed mostly against the Chitradurga belt along the boundary fault (Ghosh Roy and Ramakrishnan, 1985), but at places a thin strip of gneiss intervenes (e.g., Pitlali gneiss). The main lithology is metabasaltic amphibolite, tuffaceous para-amphibolite, calc-silicate rock, marble, fuchsite quartzite, cordierite-anthophyllite rock, manganiferous chert and BIF. The intensely mylonitised gneisses along the boundary fault mark a ductile shear zone with sinistral sense of movement, as best seen in Gayatri Reservoir near Javanahalli and at Markonahalli near Kunigal. These gneisses were mistaken earlier for paragneisses. Javanahalli band is broken up into a series of enclaves in Sira-Kallambella and Tarur areas. The Tarur calc-silicates are widespread and were locally called 'Tarurites'. All these supracrustal rocks are intensely folded and migmatised.

**Kunigal Band:** A narrow band (1.5 km wide and 30 km long) of schists near Kunigal and Huliyurdurga occurs to the east of the boundary fault in the southern strike extension of Javanahalli belt. The rock types are nearly identical to that of Javanahalli band. An interesting rock type seen here is calc-silicate quartzite studded with round grains of bottle green uvarovite-grandite garnet. The schist band has a prominent synclinal closure near Kunigal and is deflected around granite in the south of Huliyurdurga. The well-known Bandihalli enclave occurs to the west. A linear string of enclaves occurs to the east extending up to Malavalli.

**Other Bands:** A long discontinuous line of schists is exposed to the west of Closepet Granite near Ghattaparthi and Parasurampur that are similar to those of Javanahalli belt. Similarly, there are numerous enclaves of high-grade schists bordering the Closepet Granite like those of Kodamballi, Bidaloti, Saggere etc., which are similar to these transitional bands. Even the enclaves that occur in strike continuity around Talakad, Gundlupet and Gopalaswami Betta may belong to the transitional suite. Similar suites of enclaves are seen within the charnockites at Maddur-Malavalli, Satanur-Halagur, Kollegal, B.R.Hills up to Sathyamangalam, and from Kanakapura to Thattakkarai, as we proceed towards the MBASZ. All these enclaves forming discontinuous, parallel belts appear to belong to Chitradurga Group, metamorphosed under amphibolite to granulite facies rather than to Sargur Group. Detailed studies are necessary to verify this possibility.

## Classification in EDC

A synoptic stratigraphy of EDC is given in Table 3D-2 and the component units are described below:

**Older Gneisses:** Recognisable areas of older gneisses are not widespread in the EDC in contrast to their extensive development in WDC. Isolated U-Pb zircon dates of over 3000 Ma are seen in some gneissic outcrops along the western and eastern margins of some greenstone belts like the Kolar and Ramagiri that are putative basements (?). There are ~2700 Ma old banded gneisses, which are scattered but of widespread distribution and represent the oldest recognisable units. Their mutual relation with the greenstone belts is a matter of debate.

**Warangal Group:** Remnants of older supracrustals are clearly seen in the transition zone between the greenstone terrain of EDC and Karimnagar granulite belt. Important belts of older supracrustals are seen in the north of Cuddapah basin at Yarraballi, Walmidi and Ghanpur near Warangal, and Mirialguda near Nalgonda. The lithologies mainly belong to a quartzite-pelite-carbonate suite, consisting of fuchsite quartzite, quartz pebble conglomerate, cordierite-sillimanite gneiss, cordierite-anthophyllite rocks, sapphirine-kornerupine-spinel rocks, calc-silicate rocks, marbles and BIF. Amphibolites and ultramafic talc-tremolite schists are generally subordinate, but abundant locally. Komatiites are not so far reported from these belts. These suites are comparable to the Sargur Group, but for the lesser development of mafic-ultramafic suites, and are named as Warangal Group. This group has parallel trends to those of Dharwar schist belts and has similar metamorphic and migmatitic history. The significant difference is that Warangal Group occurs to the east of Eastern greenstone belts, whereas the eastern margins of these individual greenstone belts do not have QCP suite and therefore the Warangal Group enclaves may be older. Warangal Group is also different in composition from the Dharwar QCP suite occurring on the western margin of Kolar and Ramagiri belts (Sakarsanahalli, Lepakshi). However, the scattered enclaves in the gneissic terrain of mafic-ultramafic schists, BIF, quartzite, cordierite-anthophyllite-sapphirine rock and corundum-pyrophyllite rock found around Ramagiri, Kalyandurga, Jadcherla etc. may belong to Dharwar suite rather than Warangal Group, but the distinctions are tenuous.

### Greenstone Belts of Dharwar Supergroup

The EDC is characterised by volcanics-dominated, sediment-impoverished and gold-rich greenstone belts, in contrast to those of WDC. These greenstone belts are engulfed on all sides by younger granitoids. They are popularly known as Eastern greenstone belts because of their geographic position in the craton. Unlike the Western schist belts, basement-cover unconformities are not present in the Eastern greenstone belts, but a thin, disrupted horizon of quartzite-pelite-carbonate suite occurs in the modified basement gneisses at the western margin of some greenstone belts (e.g., Sakarsanahalli enclaves near Kolar belt, Lepakshi enclaves in Ramagiri belt and Gurgunta (?) enclaves near Hutti belt). The presence of orthoquartzite-carbonate suite suggests that the depositional margin was not very far from the present boundary of the greenstone belts.

In the WDC, Dharwar Supergroup is divided into Bababudan and Chitradurga Groups. Such a division is not as clear in EDC despite recent geological mapping, largely due to the volcanic ensembles forming the bulk with no marker horizons to divide them on a scale suitable for regional correlation. Only the Yeshwantanagar Formation of Sandur belt has similarities with Bababudan Group. It is intruded by granites as in the case of Hagalvadi area of Javanahalli belt. In the other Eastern greenstone belts, the Bababudan Group is not distinguishable from surrounding enclave suites. Most of the discrete greenstone belts of EDC are correlatable with Chitradurga Group of WDC. Kolar belt is regarded as the type area and the rocks are called Kolar Group. Local stratigraphic groups, named after particular greenstone belts, like Hutti Group, Sandur Group etc. are current in literature. A consolidated, composite stratigraphy for these Eastern greenstone belts has been proposed here for a broad comparison with that of WDC (Table 3D-5).

The greenstone belts of EDC form linear arrays of what may be called superbelts or composite belts that extend underneath the Cuddapah basin. The superbelts consist of more than one separate schist belt or band. The isolated, but important Sandur schist belt, which is sited over the intrusive

**Table 3D-5.** Composite stratigraphy of the greenstone belts of EDC

| | | | |
|---|---|---|---|
| | | | Proterozoic mafic dykes<br>Charnockites (2500-2600 Ma)<br>Dharwar Batholith (2500-2700 Ma) |
| DHARWAR SUPERGROUP (2600-2800 Ma) | KOLAR GROUP (Chitradurga Group) | Champion Gneiss | Felsic volcanics and volcanoclastics, volcanogenic polymict conglomerates, minor metabasalts and BIF |
| | | Goldfield Volcanics | Bimodal mafic-felsic volcanics, pyroclastics, komatiites, BIF, cherts, greywackes, pelites, carbonate rocks and minor polymict conglomerates with basic-ultrabasic intrusives |
| | | Sakarsanahalli Formation | Quartzites, manganiferous marbles, stromatolitic carbonate rocks, calc silicate rocks, pelitic schists with cordierite, andalusite, staurolite and garnet, cordierite-anthophyllite rocks (Mg-Al pelites) amphibolites, BIF and basic-ultrabasic sills |
| | Yashwantanagar Formation (Bababudan Group) | | Mafic-ultramafic rocks, quartzites, BIF |
| | | | Basement not seen (>3000 Ma) |

Closepet Granite, does not belong to the linear array. Sandur belt is however linked to Penakacherla belt through a train of enclaves. The linear arrays of superbelts in the EDC are the following:

(1) Ramagiri-(Penakacherla-Sirigeri)-Hungund superbelt
(2) Kolar-Kadiri-Jonnagiri-Hutti superbelt
(3) Veligallu-Raichur-Gadwal superbelt

Other minor greenstone belts in EDC are: (1) Manglur belt in the north of Hutti and Raichur belts, (2) Peddavuru belt to the east of Gadwal belt, (3) Medavaram band to the east of Devarkonda, and (4) Tsundupalle belt to the east of Veligallu belt, and (5) Penumuru belt in the south near Chittoor.

Description of individual belts and superbelts is given below:

**Sandur Schist Belt:** It is a prominent boat-shaped (Fig.3D-19a,b) belt (60x20 km) sited over the northern part of Closepet Granite. Recent studies have shown that it exposes a succession younging from southwest to northeast, which appears to have been thickened considerably by thrusting. The lithological association in this belt is similar to that of the Chitradurga belt, with different types of sediments in the margins and a volcanic complex in the middle. In the

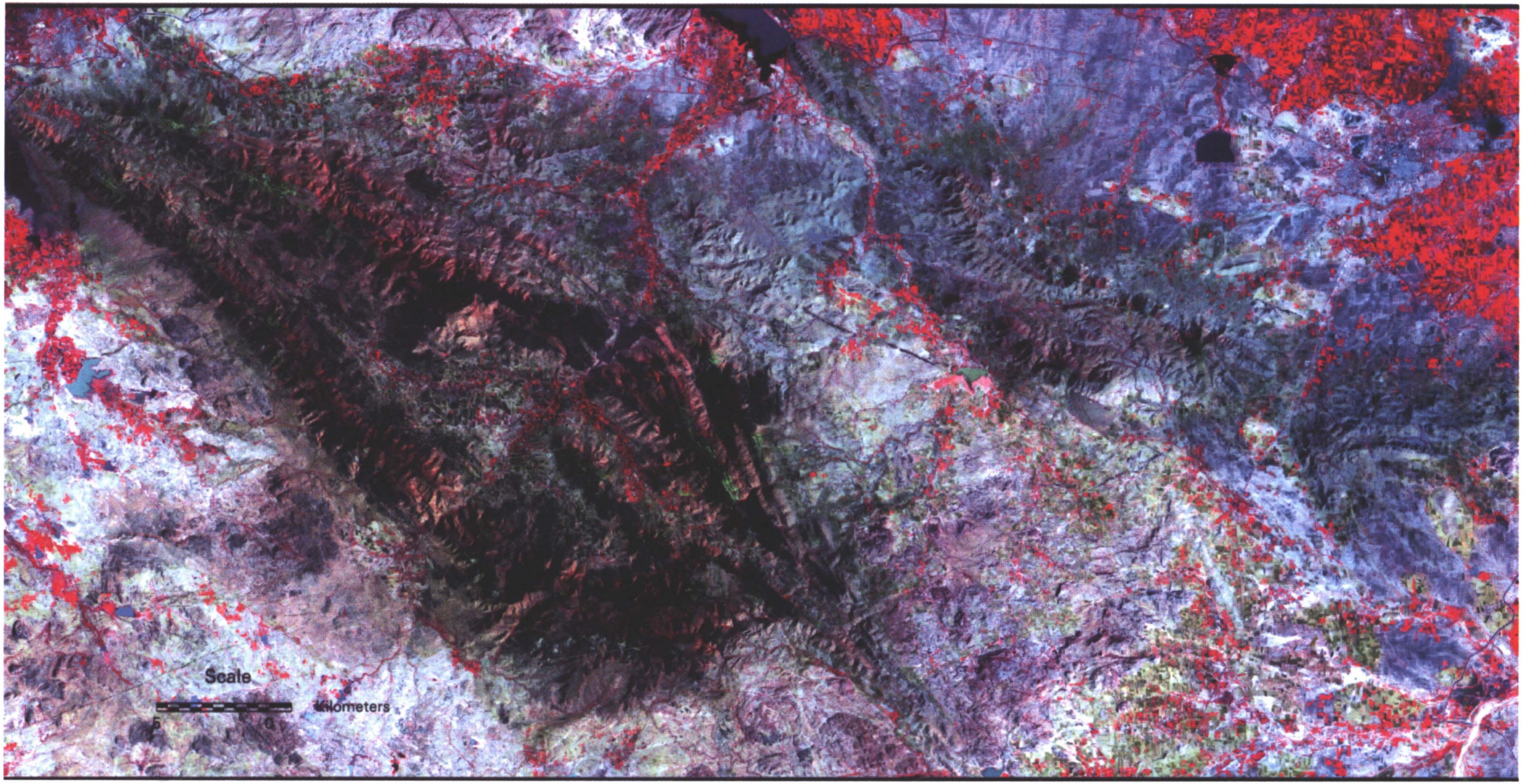


**Fig.3D-19a.** Imagery of boat-shaped Sandur schist belt, BIF bands stand out as prominent ridges. Light coloured areas denote younger granites of Dharwar batholith. A prominent BIF band is also seen in the eastern limit of the schist belt. (Courtesy: Geol. Surv. India).

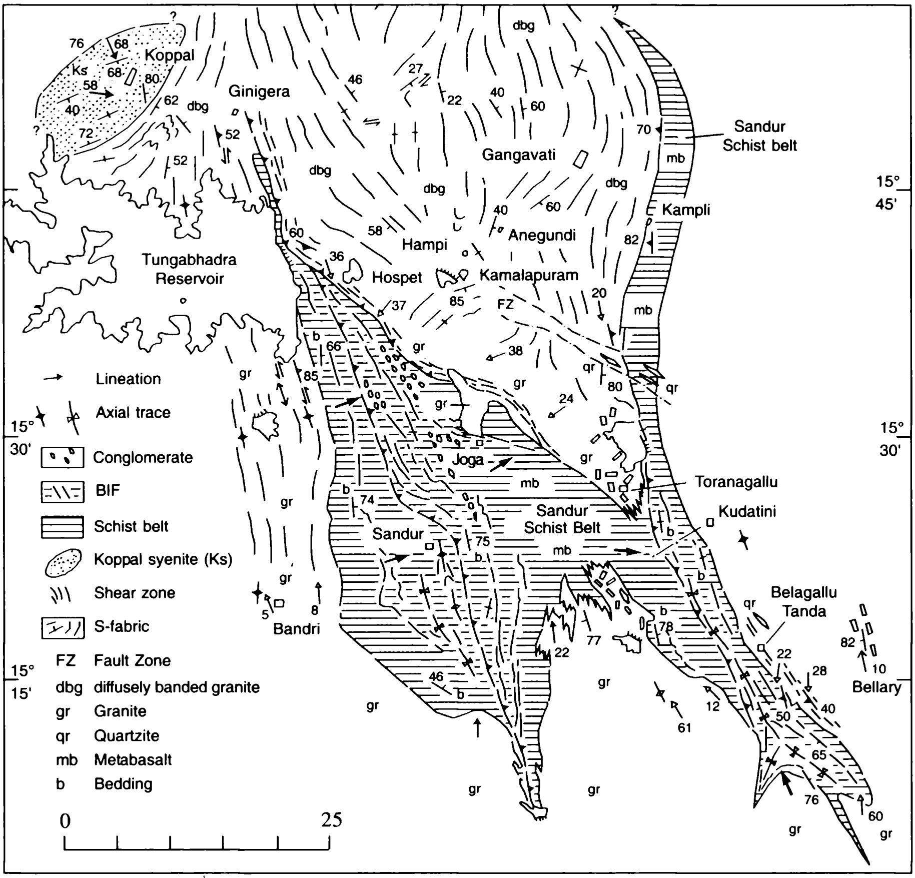

Koppal
Ks
Ginigera
Gangavati
Sandur Schist belt
mb
Kampli
dbg
Hampi
Anegundi
Hospet
Kamalapuram
FZ
Tungabhadra Reservoir
gr
qr
Joga
Sandur
Sandur Schist Belt
b
Toranagallu
Kudatini
Belagallu
Tanda
Bellary
Bandri
15° 45'
15° 30'
15° 15'
Lineation
Axial trace
Conglomerate
BIF
Schist belt
Koppal syenite (Ks)
Shear zone
S-fabric
FZ Fault Zone
dbg diffusely banded granite
gr Granite
qr Quartzite
mb Metabasalt
b Bedding
0
25

**Fig.3D-19b.** Geological map of Sandur schist belt (after Chadwick et al. 1996).

southwest margin of the schist belt, amphibolites and ultramafics abound, associated with rare quartzites (Yeshwantanagar Formation), which correlate with the Bababudan Group of WDC, but for the main difference that these rocks are intruded by gneissic veins, as in Javanahalli belt. The overlying Deogiri Formation consists of manganiferous and calcareous greywackes with convolute bedding, cross-bedded quartzites, stromatolitic limestones, volcanics and BIF, similar to the Vanivilas Subgroup of the Chitradurga Group. The succeeding unit of Raman Mala and Doni Malai Formations consist essentially of pillowed basic volcanics and BIF with minor greywackes. The normally cherty BIF is associated with an unusual granular type BIF (called GIF) reported by Manikyamba (1998). The GIF contains fragments of chert and iron oxide, and shows graded bedding. GIF is usually a Proterozoic-type iron formation, but is developed in this Archaean belt, confirming diachroneity in crustal evolution. The succeeding Taluru (or Sultanpura) Formation is a volcanic complex with pelagic sediments, polymict conglomerates, cherts and BIF, similar to the deeper water facies of Vanivilas Subgroup (e.g., Ingaldhal in the central arc of Chitradurga belt). The pillowed mafic volcanic rocks are tholeiites and high-Mg basalts. Trace element, REE and Nd isotopic data suggest their derivation from primitive mantle, and contaminated by continental crust. The associated tremolite-actinolite schists of Taluru Formation are visualised as layered basic intrusions by one school, and as komatiites, like those commonly found in the other Archaean greenstone belts, by another school. The tremolite-actinolite schists are geochemically komatiitic in composition, but confirmation by textural evidences and detailed mapping is necessary to resolve this issue. This is important because tremolite, actinolite, anthophyllite, cummingtonite etc are usually metamorphic amphiboles of needle-like habit that form sheaves and resemble the igneous spinifex texture. Taluru and Vibhutigudda Formations are similar to the Hiriyur Formation. In Taluru Formation volcanics are dominant. Vibhutigudda Formation consists of greywackes, polymict conglomerates, cross-bedded quartzites, BIFs, metabasalts, and acid volcanics that are closely inter-bedded with granite-clast volcanic conglomerate. Spectacular felsic volcanic breccias are seen in Belikallu Gudda and Sanganakallu. The association of felsic lavas, pyroclastics and volcanic conglomerates is similar to Champion Gneiss forming the eastern tectonic margins of most of the Eastern greenstone belts.

SHRIMP U-Pb ages of intrusive granites are in the range of 2500-2600 Ma, which is supported by Pb-Pb age of Deogiri limestone of ~2500 Ma and felsic volcanics of Vibhutigudda Formation at ~2600 Ma. The mafic volcanics, like those of Chitradurga 'arc', yield poorly constrained younger Rb-Sr ages that may be an artifact of alteration.

### *Sedimentation*

Quartzites, stromatolitic limestones and BIF occurring in the lower part of the sequence indicate shallow marine setting. The greywacke-polymict conglomerate unit represents turbidites and debris flows. GIF (Granular Iron Formation) represents transgression-regression cycles related to submarine volcanism. The central volcanic complex marks major event of submarine volcanism. The granite clasts in the polymict volcanic conglomerate are similar to those of the surrounding intrusive granites, suggesting rapid unroofing of the terrain.

### *Structure*

Originally the greenstone belt was described as a double syncline with an intervening anticline. Recent structural studies have shown that the eastern and western arms of the belt represent upright synclinal sheath folds, both folds being separated by a steepened thrust called the Sandur valley discontinuity. The effects of deformation are more severe in the marginal meta-sedimentary units than in the central volcanic complex that has experienced only low strain.

### Ramagiri-Penekacherla-Sirigeri-Hungund Superbelt

This superbelt consists of two discontinuous stretches of greenstone belts, namely Ramagiri-Penakacherla-Sirigeri greenstone belt and Hungund greenstone belt which are described separately below:

**Ramagiri-Penekacherla-Sirigeri Greenstone Belt:** Ramagiri greenstone belt is studied in detail in the central part near Ramagiri and Penekacherla because of gold mineralisation. The greenstone belt extends in the north up to the Tungabhadra River. The northern extensions are variously called as Penekacherla belt, Pamidi belt, Penner-Hagari belt and Sirigeri belt. The greenstone belt is narrow and linear, with bulges around domes and external diapirs of gneisses, and is split into smaller arms due to gneissic intrusions and presence of shear zones. The regional stratigraphy consists of three main units, viz., the lower, middle and upper. The lower unit in the southwest consists of mafic-ultramafic rocks (some are flows), layered basic intrusions, quartzites, calc-silicate rocks, siliceous schists and BIF. These rocks occur also as screens close the western margin near Lepakshi. This unit may correspond mainly to the lower sections of Chitradurga Group, with subordinate basal sections away from the main belt that may belong to Bababudan Group. The middle unit consists of pillowed metabasalts, chlorite-sericite schists and BIF, forming the bulk of the greenstone belt. The upper unit consists of greywackes, BIF and mafic-felsic volcanics and pyroclastics (Fig.3D-19c). The greywackes show graded bedding and colour lamination characteristic of turbidites. Limestones and dolomites are locally seen. The middle and upper units correspond to the top portions of Chitradurga Group of WDC.

The metavolcanics are mainly tholeiites with variable REE patterns in different horizons suggesting significant differences in the extent of partial melting of mantle sources (Manikyamba et al. 2004). The felsic volcanics are of dacitic to rhyolitic composition with large REE abundances and fractionated HREE. They are probably produced by shallow partial melting of arc-like basalts. The greywackes have high silica, low index of alteration (CIA) and enriched to fractionated REE patterns with no Eu anomaly.

Ramagiri-Penakacherla belt is intruded by a variety of granites and gneisses. The gneisses of Cherlapalle and Marutla domes give Rb-Sr isochron

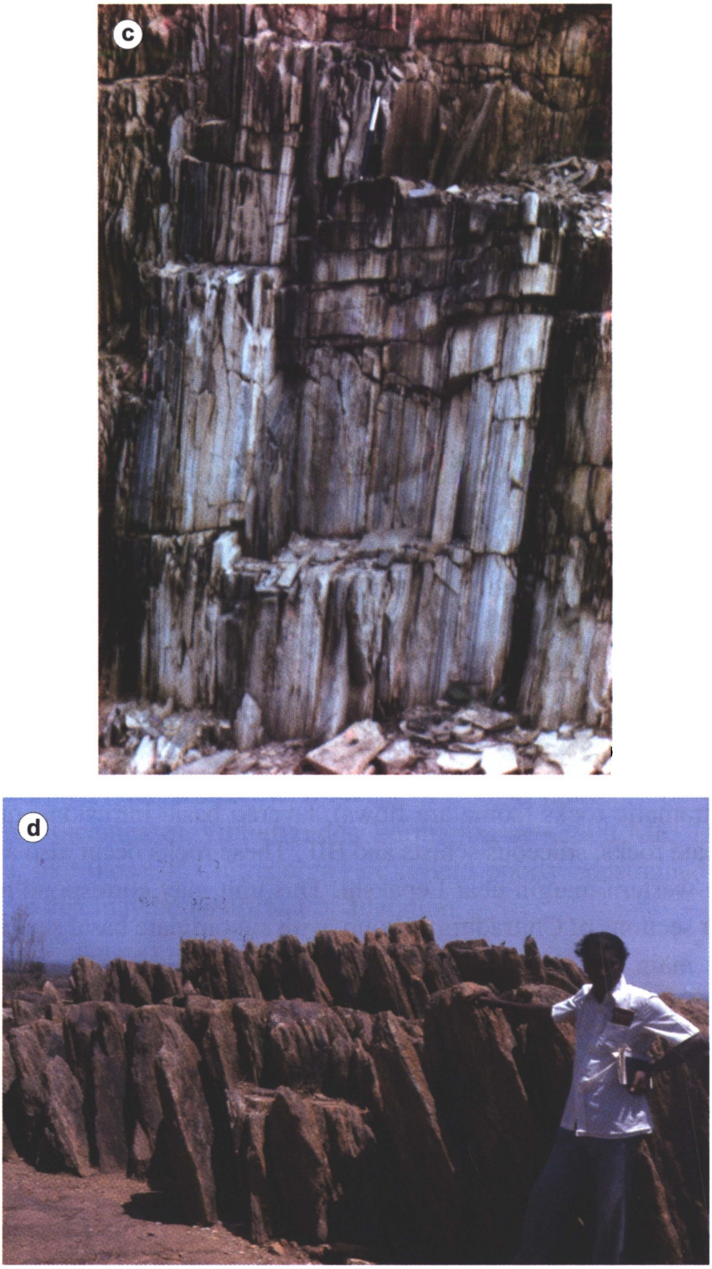


**Fig.3D-19.** (**c**) Chert-tuff association at Ramagiri (**d**) Quartz porphyry in Hungund belt.

ages of ~2700 Ma. The gneisses surrounding the belt show U-Pb sphene ages of 2550 Ma. The basic volcanics yield Pb-Pb isochrons of 2700-2800 Ma.

Gold mineralisation in quartz-ankerite-calcite veins is confined to subsidiary fault zones related to the main shear zones bounding the greenstone belt.

**Hungund Greenstone Belt:** Hungund belt, also known as Kushtagi belt, is separated from the Ramagiri-Sirigeri belt by a narrow zone of granitoids along the Tungabhadra River and is concealed in the north beneath the Proterozoic Kaladgi basin. The belt is dominated by metabasalts along the margins and a metasedimentary unit in the middle. Felsic volcanics (Fig.3D-19d) underlie the metasediments, which are mainly greywacke-phyllite with polymict conglomerate, BIF and ferrodolomite bands. Pyroxenite-gabbro-anorthosite intrusions occur in western part of the belt.

Geochemical studies (Naqvi et al. 2006) have shown that the metavolcanics are extremely diverse in composition from high-Mg to high-Fe basalts, high-Mg andesites of boninitic affinity and sodic plagioclase-quartz rich felsic rocks similar to adakites with $Na_2O$ of 4-6%. The adakites resemble TTG suites, which are interpreted as products of partial melting of basaltic slab. It is believed that partial melting of mantle source and of slab basalt has caused the compositional diversity of volcanics in the belt.

### Kolar-Kadiri-Jonnagiri-Hutti Superbelt

The Kolar, Kadiri, Jonnagiri and Hutti greenstone belts are aligned discontinuously along a linear, arcuate trend of the superbelt. Kolar and Hutti belts are better studied among these belts in view of rich gold mineralisation.

**Kolar Greenstone Belt:** The southernmost of the belts is Kolar (Fig.3D-20a), which is a narrow linear schist belt (80x2 km) intruded by diapiric granites of Patna and Bisanattam, and by granodioritic gneisses on all sides. Kolar belt graduates in the south into the charnockitic terrain near Krishnagiri (Fig.3D-20b). It is regarded as the type area for Eastern greenstone belts and Kolar Group is correlated with Chitradurga Group of WDC. The main formations of the Kolar belt are known in early literature as the "Kolar Amphibolite Series," consisting of amphibolites of various textures – granular, massive, tufted and schistose. The amphibolites yield Pb-Pb isochron ages of ~2700 Ma, like the Ramagiri volcanics. The stratigraphy of Kolar belt, like the other greenstone belts and schist belts of the Dharwar craton, shows younging from west to east. The succession commences in the west with enclaves and screens of Sakarsanahalli Formation near Kamasandra. The formation consists of amphibolites, BIF, cordierite-sillimanite-fuchsite quartzites, calc-silicate rocks, manganiferous chert and carbonate, and BIF as seen at Mallappakonda and Yerrakonda. This succession corresponds to the Vanivilas Subgroup of WDC. The overlying pillowed, agglomeratic and variolitic amphibolites are essentially tholeiites (some are Fe-rich). The tholeiites contain intercalations of high-Mg basalts of komatiitic and picritic affinities along with pyroxenitic

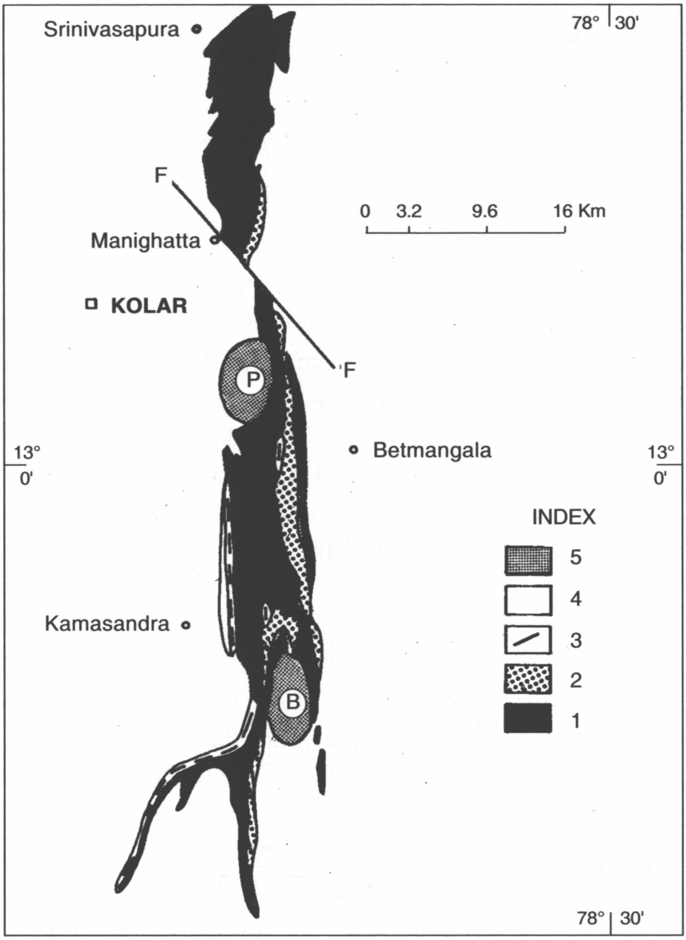


**Fig.3D-20a.** Geological sketch map of Kolar schist belt (after Viswanatha and Ramakrishnan, 1981a). **1** - mafic rocks (Goldfield volcanics), **2** - volcanoclastic sediments (Champion Gneiss), **3** - banded ferruginous chert (BIF), **4** - granite and gneiss, **5** - granitic plutons (Patna (P), Bisanattam (B)), F-F Thamballi Fault.

komatiites (tremolite-actinolite-talc-chlorite schists). The mafic-ultramafic volcanics are intercalated with chloritic-sericite-graphite-pyrite schists ('black shales') associated with BIF, and fine-grained, phyllitic greywackes. BIF is mainly of oxide and sulphide facies and has been explored for gold in the past. This succession is correlatable with the Ingaldhal Volcanics of WDC. At the eastern margin of the belt occurs a prominent horizon of polymictic conglomerate and felsic volcanic-volcaniclastic suite of 'Champion Gneiss'. These rocks are intercalated with BIF, greywackes and basic volcanics and correspond to the Ranibennur Subgroup of WDC. God mineralisation occurs in the volcanic suite both as prominent mesothermal quartz-carbonate veins and minor stratiform sulphide lodes in BIF, localised in subsidiary faults related to major shear zones.

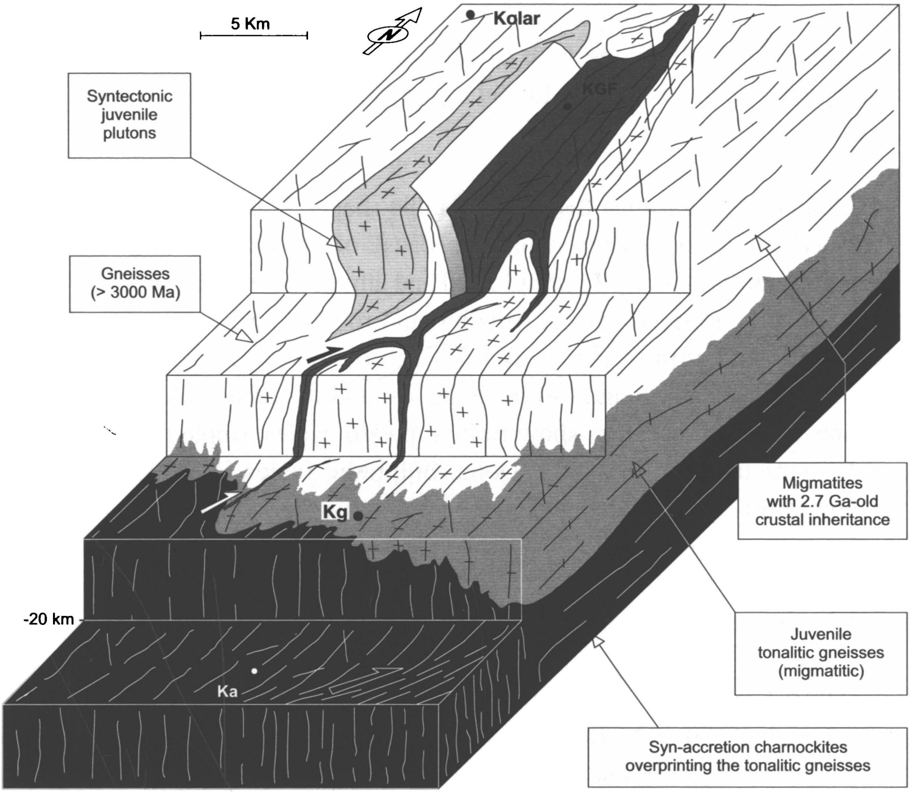

5 Km
N
Kolar
KGF
Syntectonic juvenile plutons
Gneisses (> 3000 Ma)
Kg
-20 km
Ka
Migmatites with 2.7 Ga-old crustal inheritance
Juvenile tonalitic gneisses (migmatitic)
Syn-accretion charnockites overprinting the tonalitic gneisses

**Fig.3D-20b.** Three dimensional view of southern Kolar belt grading into SGT (after Chardon et al. 2002). Ka - Karimangalam; Kg - Krishnagiri.

The gneisses and granites in the west and east of the belt indicate the presence of an older 2700 Ma unit and a younger 2550 Ma unit, as dated by multigrain U-Pb zircon method as well as by SHRIMP U-Pb zircon. The gneisses also contain rare >3000 Ma old components. These data do not confirm the subtle age differences in the terranes to the west and east of the belt, as projected in earlier literature to support plate tectonic models (Krogstad et al. 1991), describing the entire greenstone belt as a suture zone. The granitoids surrounding the schist belt are not derived by partial melting of Kolar amphibolites, but are produced from mantle-derived magmas. The parental magmas of the gneisses could be high-Mg andesites and monzodiorites called sanukitoids.

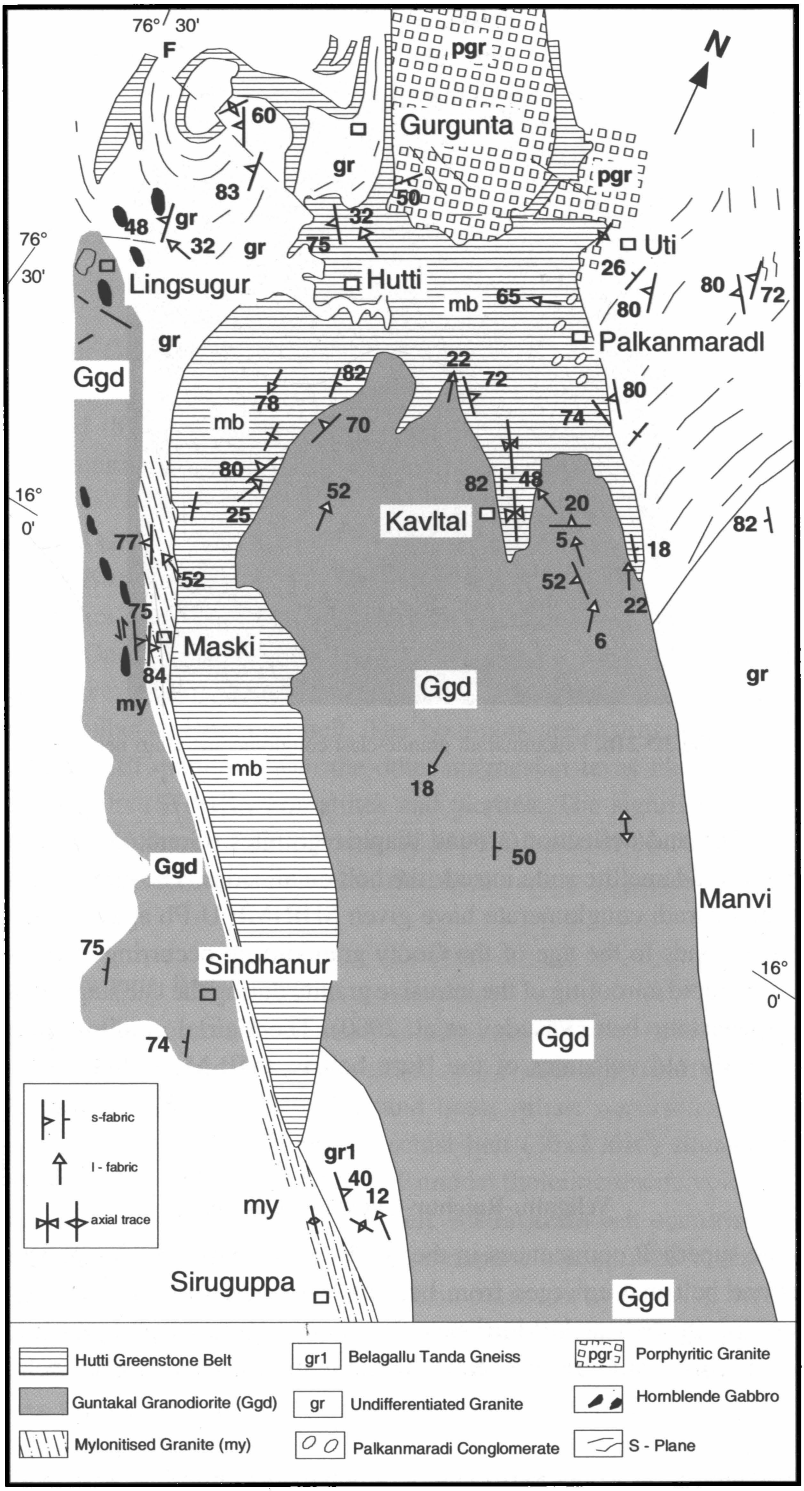
**Kadiri Greenstone Belt:** The narrow linear Kadiri belt (75x2.5 km) forms in the northern extensions of Kolar greenstone belt, with a small gap of granitoids in between, and disappears under the Cuddapah basin in the north. The belt consists mainly of acid volcanics (rhyolite, quartz-felspar porphyry and tuffaceous quartz-sericite schist) with polymict, granite-clast, volcanic conglomerates (Champion Gneiss), siliceous chlorite-sericite schists, tuffs and greywackes and BIF, along with subordinate basic volcanics. The geological setting of this belt is similar to that of the Kolar belt and corresponds to the Chitradurga Group.

**Jonnagiri Greenstone Belt:** This spindle shaped belt, situated to the north of Gooty, has recently been mapped because of gold-copper mineralisation. The belt is composed mostly of pillowed and amygdular basic volcanics, basic-ultrabasic sills, felsic volcanics (rhyolite and rhyodacite), oxide and sulphide facies BIF and minor siliceous tuffs (chlorite-sericite-quartz schists). Metabasalts are Fe-rich and low-K tholeiites, and the felsic volcanics are calc alkaline. Felsic pyroclastics show fining-upward cycles, ripple marks and cut-and-fill structures as seen near Dona. Sulphidic facies BIF and associated volcanics host sporadic gold and copper mineralisation. The belt is intruded by tonalite-granodiorite-adamellite-granite plutons. The sigmoidal shape of the belt is due to an early overturned fold refolded by upright folds. The belt has a strongly sheared eastern margin.

**Hutti Greenstone Belt:** This is the northernmost extension of Kolar greenstone belt (Fig.3D-21a) and is rich in gold mineralisation. It is also called Hutti-Maski belt with southern extension to Siruguppa. The belt covers an area of about 670 km$^2$ and consists of a predominant basic volcanic suite with tuffaceous chlorite schists and minor BIF, and a younger unit rich in basic-acidic volcanics, greywackes and polymict, granite-clast conglomerates. The felsic volcanics-polymict conglomerate unit called Palkanmaradi conglomerate (Fig.3D-21b) corresponds to the Champion Gneiss of Kolar belt. The basal amphibolites are fine-grained and banded, overlain by amygdular and pillowed metabasalts. The mafic volcanics are mainly Fe-rich tholeiites enriched in LREE. Flows or sills of basaltic komatiite composition are common. Quartzite, phyllite, limestone and calc-silicate rock are intercalated with the basalt-greywacke suite. The sediments are locally metamorphosed to andalusite-cordierite-biotite-garnet-staurolite schists.

Another important aspect is the presence of an enclave cluster of high-grade schists in the northwest called the Gurgunta (or Parampur) belt and in the area to the west of Maski. These enclaves, earlier regarded as part of the older sequence of Sargur Group, are now found to be part of Hutti Group and may be correlated with the Vanivilas Subgroup of Chitradurga Group. The main rocks of the enclaves are amphibolite, BIF, fuchsite quartzite and staurolite-garnet quartzite. Spodumene concentrations are noted in pegmatites that intrude the belt.

The hook-shaped configuration of the belt to the north is a result of


76° 30'
F
pgr
N
60
Gurgunta
gr
83
50
pgr
48
gr
32
32
gr
75
Uti
76° 30'
Lingsugur
Hutti
26
80
72
mb
65
80
gr
Palkanmaradl
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22
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5
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18
52
52
22
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6
Maski
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Ggd
Manvi
75
Sindhanur
16° 0'
74
Ggd
s-fabric
l - fabric
axial trace
gr1
40
12
my
Siruguppa
Ggd
Hutti Greenstone Belt
Guntakal Granodiorite (Ggd)
Mylonitised Granite (my)
gr1
Belagallu Tanda Gneiss
gr
Undifferentiated Granite
Palkanmaradi Conglomerate
pgr
Porphyritic Granite
Hornblende Gabbro
S - Plane

**Fig.3D-21a.** Geological map of Hutti schist belt (after Chadwick et al. 1999).

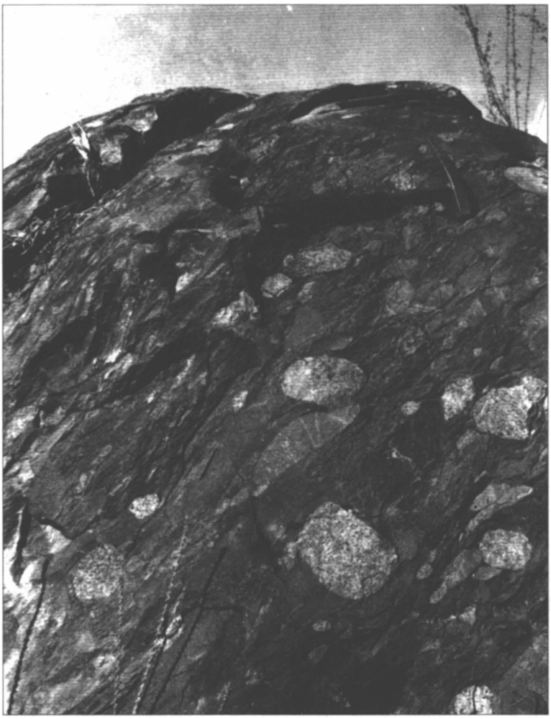


**Fig.3D-21b.** Palkanmaradi granite-clast conglomerate, Hutti belt.

cross folding and deflection around diapiric granites. Granitoids of tonalite-granodiorite-adamellite suite intrude the belt on all sides. The granitic clasts in the Palkanmaradi conglomerate have given SHRIMP U-Pb age of ~2600 Ma that corresponds to the age of the Gooty granodiorite occurring in the south, suggesting rapid unroofing of the intrusive granite during the late stage evolution of the greenstone belt (Vasudev et al. 2000). The Kairtal granitoid intruding the 2600 Ma old volcanics of the Hutti belt is 2550 Ma old (Rogers et al. 2007).

### Veligallu-Raichur-Gadwal Superbelt

The superbelt commences in the south as two parallel arms of Veligallu greenstone belt that emerges from beneath the Cuddapah basin in the north as a composite belt at Veldurti near Kurnool. It bifurcates again into two divergent arms at Veldurti, viz., Raichur belt in the west and Gadwal belt in the east.

**Veligallu Greenstone Belt:** This is a coherent belt (60x8 km$^2$) split into two parallel arms by the intervening intrusive granite, and continues in the north right up to the boundary of the Proterozoic Cuddapah basin, and peters out in the south as slivers in granites. The belt consists essentially of metabasaltic amphibolites with pillows and amygdales, minor ultramafic schists and BIF in the lower portion in the west and a smaller unit of felsic volcanics and pyroclastics including a polymictic conglomerate (Champion Gneiss) and BIF in the east. Chloritoid is seen in felsic schists and pyrophyllite occurs in bedded tuff. The belt is intruded by granitoids containing some small patches of banded gneiss.

**Raichur Greenstone Belt:** This (75x6 $km^2$) belt, also called Deodurg belt, consists of low K, low Ti tholeiitic metabasalts with subordinate felsic volcanics (dacites and rhyodacites) and cherts. Numerous meta-basaltic amphibolite enclaves occur near Deodurg and between Shorapur and Shahpur.

**Gadwal Greenstone Belt**: This belt (85x3 $km^2$) extending up to Narayanpet (also called *Narayanpet belt*) is also made of pillowed to massive metabasalts, felsic volcanics, volcanoclastics, BIF and volcanic conglomerate of Ulindakonda (Champion Gneiss). Recent geochemical studies in this belt (Manikyamba et al. 2005) have identified the presence of boninites, Nb-enriched basalts and adakites, similar to Hungund belt. The boninites are distinguished by trace element and REE patterns from the other magnesian lavas like the siliceous high-Mg basalts (SHMB), komatiites and picrites. The significant chemical signatures are U-shaped REE patterns, $Al_2O_3/TiO_2$ ratio of 30-50 and low Nb, Ta and Ti. These schists are also intruded by a variety of granites.

## Minor Greenstone Belts

**Manglur belt** occurs to the north of Hutti and Raichur belts and consists of tholeiitic basalts and felsic volcanics, along with polymict, granite-clast conglomerates (Champion Gneiss) and hosts minor occurrences of gold. **Peddavuru belt** is a small U-shaped schist belt (30x2 $km^2$) situated on the northern fringe of the Cuddapah basin. Bimodal tholeiitic-dacite volcanics and BIF form the main litho-units of this belt. **Medavaram belt** occurring further east consists of metabasalts and BIF. **Tsundupalle belt** situated to the east of Veligallu belt in the south of Cuddapah basin occurs as two parallel bands, and consists essentially of metabasaltic amphibolites, gabbroic sills and acid lavas. Besides these numerous narrow bands, several scattered Dharwar (?) schist enclaves are seen in the granitic terrain (EDC) consisting of corundum-pyrophyllite assemblages, cordierite gneisses, amphibolites and ultrabasic rocks. **Penumuru belt** occurring near Chittoor in the south consists of amphibolites, sillimanite-quartz schists and minor ultramafics.

### Karimnagar Granulite Belt

This granulite belt occurs on the southern shoulder of the Godavari graben, corresponding to the Bhopalpatnam granulite belt on the north of the graben in Bastar craton. It consists of charnockites, basic granulites, granites, gneisses and scattered enclaves of fuchsite quartzites, sillimanite-cordierite-garnet quartzites, sapphirine-kornerupine rocks, marbles and BIF, with subordinate mafic-ultramafic rocks. A rare occurrence of quartz pebble conglomerate occurs near Nimilikonda. These supracrustal rocks, though concordant with the Dharwar trend, belong to Warangal Group. The granulite belt shows gradual transition from the greenstone terrain without any tectonic discontinuity. The charnockites of Karimnagar belt yield Dharwar ages (~2500 Ma) similar to the cratonic charnockites occurring in the north of Palghat-Cauvery shear zone.

### Nellore-Khammam Schist Belt

The Nellore-Khammam schist belt (NKSB) is the most enigmatic schist belt of EDC that has trends parallel to the Eastern Ghats mobile belt (*see* Ramakrishnan, 2003a). This schist belt abruptly emerges as a large belt in the east, towards which Dharwar belts become progressively narrow and attenuated because of post-Dharwar, pre-Cuddapah denudation. The Nellore-Khammam belt is therefore younger than Dharwar greenstone belts. It occurs in the transition zone between the Dharwar craton and the Eastern Ghats Mobile Belt (EGMB), and is therefore described in Chapter 4.

### High Grade Enclaves of EDC

The Eastern greenstone belts from Ramagiri belt to the Cuddapah boundary fault peter out along the strike into enclaves in the south up to MBASZ through a terrain comprising gneisses, granites and charnockite massifs. The extensions of Ramagiri and Kolar greenstone belts are seen as enclaves up to Bhavani via Mettur dam. These enclaves consist of fuchsite-sillimanite quartzite, sillimanite-corundum rocks, BIF and tremolite-talc schist that were classified earlier under Sathyamangalam Group, but are most probably high-grade Dharwar rocks (e.g. Sakarsanahalli, Lepakshi or equivalents of Vanivilas Subgroup). Further east, a prominent cluster of enclaves is noticed near Thiruvannamalai. These enclaves occur within the charnockites and gneisses that abruptly emerge as high hills from the granitic plains of Chittoor in the south of Palar Fault, as a result of large vertical movement along the fault. The enclaves form a distinctive suite of mafic granulites (basalts and gabbros), pink quartzo-felspathic granulites and BIF (Sugavanam et al. 1978). The pink granulites may represent acid volcanics in the granulite grade. Isolated bodies of ultramafic-mafic-anorthosite suite are seen near Thorappadi, Manmalai, Mamandur and other places. Lithologically, they resemble those of Eastern greenstone belts, but occur in the granulite grade, and may be equivalent or older than the Dharwar Supergroup of EDC. The enclave suite may be tentatively called Thiruvannamalai Group (or better as Salem Group) that extends in the east up to Thirukkoilur, and to the south up to MBASZ near Salem, and up to Namakkal, along the southern strike continuity of the Cuddapah boundary fault. These enclaves were earlier correlated with Charnockite Group, but since charnockites are not specific stratigraphic entities, this nomenclature is inappropriate. The Salem Group and Warangal Group of EDC may be similar to the ultramafic-mafic belts (e.g. Nuggihalli) and QPC associations (e.g. Sargur belt) respectively, of Sargur Group in WDC reflecting vertical or lateral facies variations of the same broad sequence.

The eastern boundary of Dharwar craton in this region is marked by the presence of charnockites of Kanchipuram and Chennai (Madras), and by gneisses up to Vridhachalam. The charnockites enclose folded layers and enclaves of pyroxene granulite and garnet-sillimanite-cordierite gneisses as at Pallavaram (Sen et al. 1970; Sugavanam and Venkata Rao, 1990), close to the type area of charnockite at St. Thomas Mount (Subramaniam, 1959) that is immortalised by the monumental work of T.H. Holland in 1900, and is preserved as a National Geological Monument. The charnockites and their enclaves of this area represent the deeper parts of the craton corresponding to gneisses exposed at shallower levels between the Nellore schist belt and the Cuddapah basin at Kalahasti. The marginal zone of EGMB, by projection along the strike, may occur further east, but is concealed under the Phanerozoic coastal sediments adjoining the Bay of Bengal.

### Dharwar Batholith

Dharwar batholith consists of a series of parallel plutonic belts (*see* Narayanaswami, 1970) made of juvenile and anatectic, polyphase, calc-alkaline granite, granodiorite, monzonite, diorite and older migmatitic orthogneiss. These belts are about 15-25 km wide and hundreds of km long, with regional trends parallel to the greenstone belts. The plutonic belts are wedge-shaped and have magmatic-state or pre-full crystallisation fabrics as well as steep granitic dykes, which are typical of the well-studied Phanerozoic batholiths and hence called the Dharwar batholith by Chadwick et al. (2000), in order to distinguish them from the still widely used terminology of Peninsular Gneiss that is inappropriate because the terrain is more granitic than gneissic. The batholith has grown through inflation by syn-magmatic vertical sheets of grey granite, other syn-plutonic dykes, commingled granite and granite breccia, microgranular diorite, appinite, pegmatite and aplite. The plutonic belts are bounded either by schist belts, or zones of mylonitised granite or high-strain orthogneisses. Diffusely banded, multipulse granite dominates the plutonic belts, but some homophanous types may also be present. The plutonic belts are compositionally made of three groups of granitoids, (T. Gopal Reddy, S. Sarvothaman and others, *In:* GSI, 2006, p.308, 310; Gopal Reddy et al. 1998) viz., (1) tonalite-trondhjemite-granodiorite (TTG) suite, (2) tonalite-granodiorite-monzogranite/adamellite (TGM) suite, and (3) monzogranite-syenogranite-alkali-felspar granite-quartz syenite (MSAS) suite. The overall extent of the individual suites is difficult to ascertain, but in the northeast part of the batholith, approximately, the MSAS suite is the largest (>5000 km$^2$), followed by TGM suite (600 km$^2$) and TTG suite (350 km$^2$). Each group has its own compositional and spatial distribution, structural and textural features and type of enclaves (see also Jayananda et al. 2000; Moyen et al. 2003).

TTG suite consists of migmatitic gneisses (Fig.3D-22) forming a low K, low Rb and high Na suite, with hornblende and biotite as chief accessories. The gneisses are LREE enriched with negative Eu anomaly, and are intruded by dykes of appinite suite (hornblende-rich mafic diorite to granite) and by microgranular mafic dykes and enclaves. They are produced by partial melting of garnet amphibolite of mantle origin, along with variable contributions from the older granitic crust. Their contact with the greenstone belts is either obscured by soil cover or by younger granite intrusions. They are therefore interpreted

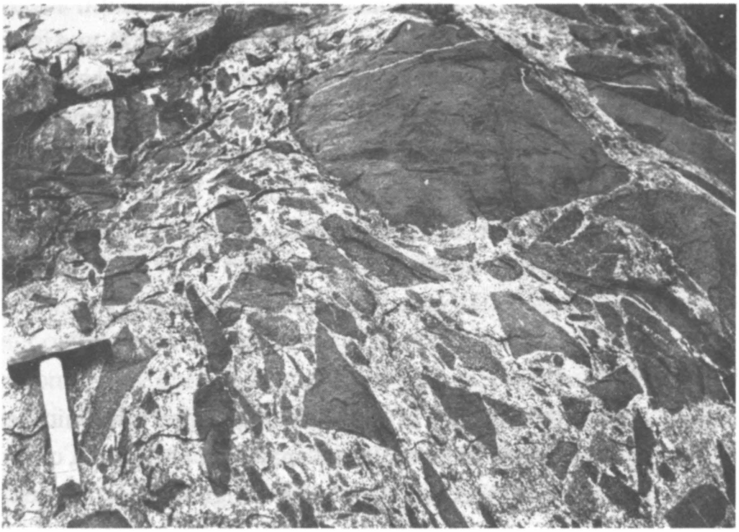


**Fig.3D-22.** Agmatitic gneiss at Kathriguppe in Bangalore.

as early syntectonic intrusions or as basement. TTG suite is best exposed as swathes and smaller enclaves in the Transition Zone between EDC and WDC, near Bangalore, to the east of Sandur belt, between Hungund and Hutti belts, south of Hutti belt, on both sides of Kolar belt, and in the gneissic domes of Cherlapalle and Marutla near Ramagiri belt. Most of these gneisses span an age range of 2700-2800 Ma as dated by SHRIMP U-Pb and Rb-Sr methods, but their protolith ages are >2900 Ma, corresponding to the main thermal event of WDC.

TGM suite consists of a diverse group of calc-alkaline, low K, high silica, metaluminous to peraluminous gneisses with ubiquitous mafic microgranitoid enclaves and subordinate hornblende diorite dykes. They have chemistry and origin similar to TTG suite. At places, they form part of the same diapiric bodies as TTGs. Some of them are sanukitoids having high Mg.

MSAS suite consists of high silica, high K granites with highly fractionated REE patterns, LREE enrichment and negative Eu anomaly. Several phases of granitic intrusions are seen in this suite, which is invariably associated with microgranite, diorite, quartz diorite and granite. Clinopyroxene occurs in the suite, besides hornblende and biotite. Orbicular granites with hornblende nuclei are also seen locally. MSAS suite is calc-alkaline having near-minimum melt composition and is formed by partial melting of the sialic crust.

TGM and MSAS suites occur as tors and ridges amidst the plains comparable to global 'granite' bloom of Davis and Blecker (1999). They are extensively quarried as dimensional stones and used widely as road metal. Drusy amethyst is found as veins in a few granites and used as semi-precious stone. The granites, dated by Rb-Sr methods at about 2550-2600 Ma, intrude the greenstone belts on large scale in the form of ballooning diapirs, as evidenced by concordant fabrics, interdigitated to rounded contacts, and by the abundance of greenstone belt enclaves in granites. The granites show magmatic banding, magmatic-state fabrics and late tectonic (crystal-plastic) fabrics during regional deformation. In many granite bodies, magmatic banding trending NE is superposed by tectonic fabric striking NW. The boundaries between the plutonic and schist belts are marked by intense shearing, and occupied by porphyritic granites becoming granitic mylonites and high-strain orthogneisses. Shear zones are dominantly sinistral, with the shear sense indicated by S-C fabrics and winged porphyroblasts.

TGM and MSAS suites were described in earlier literature as Hyderabad pink and grey granites, after their extensive development in the erstwhile Hyderabad State. The pink or red colour is attributed to the presence of hematite dust in microcline. The precipitation of iron oxide may be due to late-magmatic volatile action or post-magmatic meteoric water action and weathering. The frequent gradation from pink to grey in outcrops suggests that weathering is responsible for the colouration, which is accentuated along fracture zones to produce "brick red zones". There is no intrinsic difference between the pink and grey varieties and so the earlier colour classification needs to be abandoned.

### Younger Intrusions in EDC

The plutonic belts enclose a few scattered younger intrusions. *Joga granite* occurring within the Sandur belt contains fluorite and carbonate and yields SHRIMP U-Pb age of 2570 Ma. *Koppal syenite* is an elongate, wedge-shaped intrusion trending NE-SW, which has steep banding in contact with the host granite to the NW of Sandur belt (Chadwick et al. 2001). Syn-magmatic hornblendic pods occur parallel to magmatic banding in the syenite. Hornblende diorite and microgranular mafic enclaves are common. The syenite consists of microcline perthite, albite, hornblende, clinopyroxene and minor quartz. The syenite gives SHRIMP U-Pb zircon age of 2526 Ma. *Kallur diorite* is an elongate body (75x12 km) intruding the western margin of Raichur belt. It is a medium grained hornblende diorite that grades into porphyritic granodiorite, and is intruded by pegmatite and aplite.

### Closepet Granite

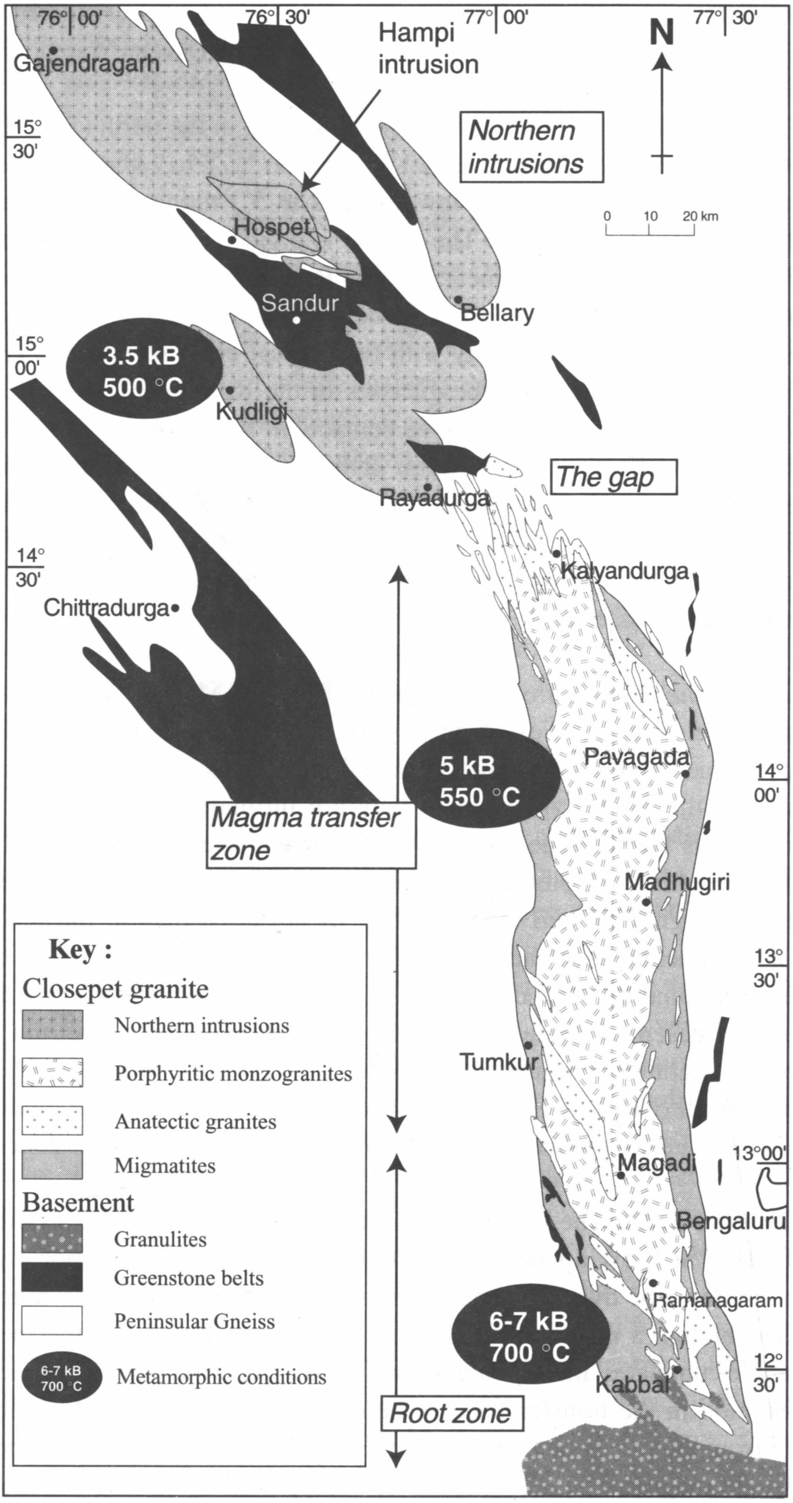
Closepet Granite is a unique linear, arcuate body consisting of diverse granitic types. The granite has easterly convexity that mirrors the configuration of the schist belts. The diffuse transition zone between WDC and EDC is visualised by some authors as terminating at Closepet Granite. There is a view that Closepet Granite is only one of the similar plutonic belts forming part of the large Dharwar batholith (Chadwick et al. 1996, 2000). However, this is the first linear younger plutonic belt of cratonic extent which occurs to the east of Chitradurga shear zone that serves as a convenient landmark to demarcate EDC from WDC and may represent a 'stitching granite' in the suture zone or geosuture. The granites occurring further east have earlier been correlated with Closepet Granite, but the long usage and voluminous literature justify the restriction of the term 'Closepet Granite' to the linear, central plutonic belt in accordance with its original definition by Smeeth (1916).

Closepet Granite (after the town of Closepet, named for Major Close, a British Army Officer, and now called Ramanagaram) represents a 400 km long and 20-30 km wide plutonic belt that is bounded by shear zones. High precision zircon ages of the granite from different laboratories define a narrow age range of 2510-2530 Ma. The granite is divisible into two parts, the southern and northern, separated near Kalyandurga by a Gap Area. The southern part extending from the Cauvery River to Kalyandurga is the better-studied main body. The northern part extends from Rayadurga to the Deccan Trap boundary (Moyen et al. 2003).

The oblique crustal section from shallow level in the north (5 to 10 km, 500 °C / 2 to 3 kbar) to deeper level (20-30 km, 700 °C/ 6 to 7 kbar) in the south in Dharwar craton, produced by low angle (2 to 5°) tilting to the north, has affected Closepet Granite also. The granite is divided into three depth zones based on the mode of emplacement, viz., (1) Root Zone, (2) Transfer Zone and (3) Intrusion Zone, with a Gap Area between the Transfer and Intrusion Zones (Fig.3D-23). In conformity with the vertical cross section, the granite has transitional contacts with the gneisses in the Root and Transfer Zones, whereas it has well-defined intrusive contacts in the Intrusion Zone. There are, however, differences of opinion about the nature of contacts, shape of the intrusion and other details, but the overall picture given by Moyen et al (2003) is broadly acceptable. At the southern end, close to the granulite facies boundary, incipient charnockites have formed in the granite, as is the case in the associated gneisses also.

*Root Zone* extends from the Cauvery River to Magadi and consists of rounded to elongate bodies of porphyritic monzogranite with subordinate clinopyroxene-bearing monzonite. Pink and grey anatectic granites grade into gneisses in the border zone where they are intimately commingled. The heterogeneous border zone has microgranular enclaves, cumulate enclaves, basement xenoliths and biotite schlieren. Geochemical modelling suggests that the mafic magma formed from melting of enriched mantle intruded the gneissic continental crust and induced partial melting, which was followed by limited fractionation. The differentiated mafic magma has mixed with the products of basement anatexis to produce the compositional spectrum from monzonite to granite. The anatectic suite has $SiO_2$ 68-76%, Mg# 0.36-0.02 and has high alkali ($Na_2O+K_2O$) contents, and shows calc alkaline differentiation trend. The anatectic granites are emplaced syntectonically in shear zones.

*Transfer Zone:* The transfer zone extends from Magadi to Kalyandurga terminating at the Gap Area, and consists of apophyses of porphyritic monzogranite and dykes of equigranular granite that grade into marginal gneisses through a migmatite zone. Enclaves of granulite facies metapelites, amphibole cumulates, microgranular mafic enclaves and K-felspar megacrysts are common in the transfer zone. The continuation of the central monzogranite from the root zone to transfer zone suggests that both the zones belong to a single magmatic suite, which is also supported by Sr and Nd isotopic studies.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Gajendragarh
Hampi intrusion
Northern intrusions
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Hospet
Sandur
Bellary
15° 00'
3.5 kB 500 °C
Kudligi
Rayadurga
The gap
14° 30'
Kalyandurga
Chittradurga
Pavagada
5 kB 550 °C
14° 00'
Magma transfer zone
Madhugiri
13° 30'
Tumkur
Magadi
13°00'
Bengaluru
Ramanagaram
6-7 kB 700 °C
12° 30'
Kabbal
Root zone
Key :
Closepet granite
Northern intrusions
Porphyritic monzogranites
Anatectic granites
Migmatites
Basement
Granulites
Greenstone belts
Peninsular Gneiss
6-7 kB 700 °C
Metamorphic conditions

**Fig.3D-23.** Vertical zonation of Closepet granite (after Moyen et al. 2003).

*Gap Area*: It is marked by apophyses of granite from the transfer zone and by abundance of granite dykes that suggests a physical link between the southern and the northern parts of Closepet Granite. Sr and Nd isotope studies corroborate the idea of physical connection. It is also interpreted that the Gap Area represents a change in the mode of emplacement from fissure fillings, dykes and sheets in the south to small plutonic bodies in the north. The ascent of deep-seated magma was probably terminated at the Gap Area where the mush was filtered, allowing only the liquid to rise to form dykes.

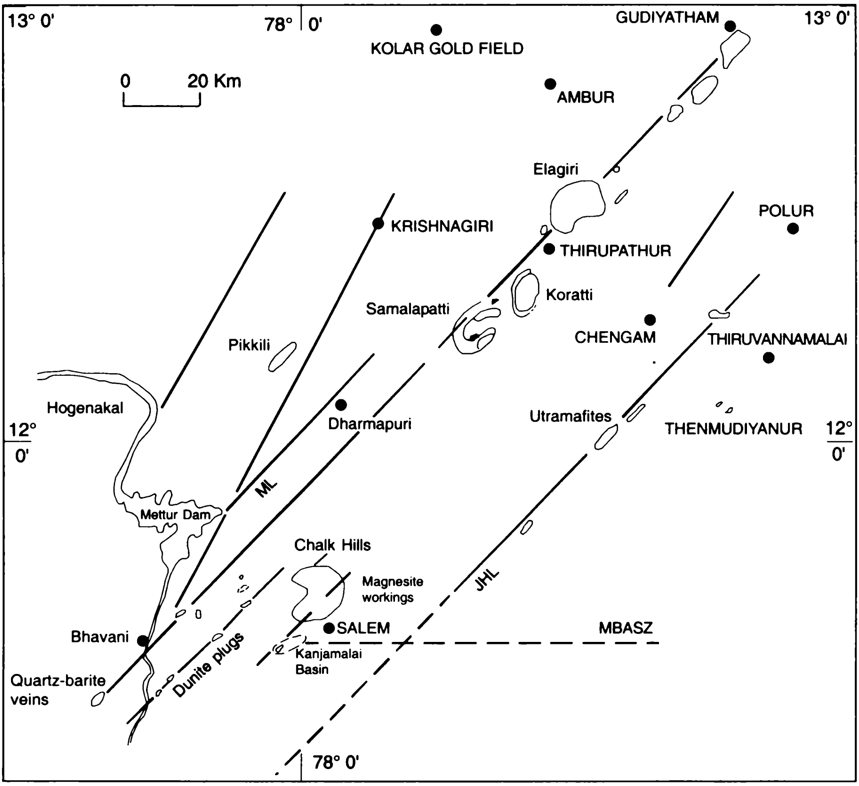
*Intrusion Zone* occurring to the north of Gap Area consists of a number of small elliptical bodies of equigranular granite. Feeder dykes developed in abundance have filled the fractures in shallow intrusions. The contact with the adjacent gneisses is sharp and devoid of effects of migmatisation.

The intrusive suite is poor in $SiO_2$ (50-68%), has high Mg# (0.46-0.32) and is rich in Ba, Sr and alkalis, and poor in Ni and Cr. REE patterns are LREE enriched and highly fractionated.

### Neoproterozoic Alkaline-Carbonatite Complexes

Alkaline-carbonatite complexes of EDC are concentrated along a prominent NNE-SSW trending, 200 km long Dharmapuri straight belt extending from Gudiyatham in the north to Bhavani in the south (Fig.3D-24). The straight belt is bounded by the Mettur (Palakode) shear zone in the west and Javadi Hills shear zone in the east. Important alkaline-carbonatite complexes of the belt are Elagiri syenite, Sevathur (Koratti) carbonatite, Samalpatti (Jogipatti) carbonatite and Pakkanadu (Jalagandapuram) carbonatite. Pikkili syenite and Hogenakal carbonatite occur nearby along parallel lineaments in the west. The alkali-carbonatite complexes are surrounded by a conspicuous zone of epidote-hornblende gneiss that may either mark an atypical fenite zone or a shear zone metasomatised by fluid ingress.

The alkali-carbonatite bodies form oval-shaped ring complexes and phacoliths. They consist essentially of syenite, carbonatite and pyroxenite, with subordinate dunite, peridotite, hornblendite and lamprophyre. Siderite-ankerite and quartz-barite veins are fairly common. Locally the syenites contain aegirine and riebeckite. They are neither felspathoidal nor quartz-rich and are therefore different from those of the Prakasam alkaline province, with which they are linked through lineaments by some authors following Drury et al. (1984). The Prakasam alkaline province occurring at the margin of EGMB is dated at 1300-1500 Ma, whereas the Dharmapuri alkaline province is 700-800 Ma old. The evolution of Dharmapuri (Tirupathur) province may be linked to the evolution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KOLAR GOLD FIELD
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AMBUR
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KRISHNAGIRI
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POLUR
Koratti
Samalapatti
CHENGAM
THIRUVANNAMALAI
Pikkili
Hogenakal
Dharmapuri
Utramafites
THENMUDIYANUR
12°
0'
12°
0'
ML
Mettur Dam
Chalk Hills
Magnesite workings
JHL
SALEM
MBASZ
Bhavani
Kanjamalai Basin
Quartz-barite veins
Dunite plugs
78° 0'

**Fig.3D-24.** Alakali-carbonatite complexes and ultramafic intrusions in Dharmapuri rift zone (after Grady, 1971). MBASZ - Moyar-Bhavani-Attur shear zone. Lineaments: ML - Mettur, JHL - Javadi Hills.

of Pandyan mobile belt and the 'Purana' basins of Kurnool, Bhima, Badami and Sullavai.

Geochemical and isotopic studies of the alkali-carbonatite complexes indicate that they have an evolved Sr and Nd composition, LILE enrichment and large negative Nb anomalies. They are probably derived from enriched sub-lithospheric mantle sources, and are differentiated from either alkali basalt, nephelinite or shonkinite magmas. The carbonate and silicate fractions probably separated at shallow levels through liquid immiscibility. Metamorphism and fluid advection also appear to have affected the complexes late in their history.

Major bodies of alkaline-carbonatite complexes are described below:

*Elagiri syenite* is a circular pluton consisting of syenite, along with ultramafic rocks, lamprophyres and rare carbonatites. Quartz-barytes veins are common. Explosive breccia occurs at the periphery of the pluton.

*Sevathur (Koratti) carbonatite* is an arcuate, two-km long body of apatite-magnetite type carbonatite, flanked by syenite and pyroxenite. The main carbonatite was interpreted by some authors as zoned cone sheets. Dykes and veins of carbonatite also occur in abundance. The carbonatite is essentially beforsite (Fe-bearing dolomite) that hosts uraniferous pyrochlore. The pyroxenite contains pockets of vermiculite.

*Samalpatti (Jogipatti) carbonatite* (40 km$^2$) is a ring like pluton with syenite in the core and pyroxenite at the periphery. Dolomitic and para-ankeritic carbonatite and benstonite (Ba-rich) are the main varieties. *Kanjanur ultramafite* at the periphery consists of pyroxenite with patches of peridotite, serpentinite, magnesite and shonkinite dyke. The syenite contains accessory garnet and wollastonite.

*Pakkanadu (Jalagandapuram) carbonatite* consists of syenite with pyroxenite and dunite. Sovite within syenite is the main carbonatite within the Jalagandapuram body having an ultramafic core.

*Pikkili syenite* is an exceptional pluton containing undersaturated syenite varieties like nepheline-, corundum-, and pyroxene syenites. Basic to alkaline dykes, felsites, syenitic pegmatites and quartz-barite veins are the common constituents of this pluton.

*Hogenakal carbonatite* occurs as parallel dykes and lenses in syenite and pyroxenite. Carbonatite agglomerate, well exposed at places, indicates explosive volcanism. This carbonatite is the oldest known body dated at ~2000 Ma, but the geological significance of this antiquity is unclear.

### *Other Intrusions*

There are several scattered intrusions of granites and syenites in the interior of EDC. Syenites, mostly hornblendic, are not alkaline. These granites and syenites are perhaps Archaean in age. Kimberlites and related rocks have been discovered in many clusters in EDC with intensification of diamond exploration. These bodies are described in the Chapter 5 (Proterozoic Sedimentary Basins).

### *Ultramafic and Anorthosite Intrusions*

There are numerous intrusions of ultramafic rocks located in NE-SW trending lineaments forming part of the Dharmapuri rift and the vicinity (Ram Mohan et al. 2000). A few important occurrences such as Chalk Hills, Thorapaddi and Thenmudiyanur will be described here. Other smaller bodies are seen near Manmalai and Thiruvannamalai.

*Chalk Hills* near Salem expose two prominent ultramafic bodies consisting of serpentinised dunite with patches of peridotite. Alkaline rocks like shonkinite intrude the ultramafics. Magnesite veins in the ultramafics are of economic importance.

*Thorappadi ultramafic complex* is an inverted V-shaped synformal body consisting of parallel bands of hornblende gabbro, norite and hornblendite intruding charnockites. The rocks are melanocratic, coarse grained and enriched in Ni, Cr, Zr and Y.

*Thenmudiyanur ultramafic complex* forms a oval-shaped zoned body consisting mainly of serpentinised dunite in the core, with patches of peridotite and veins of magnesite. Pyroxenites and hornblendites constitute the rim of the complex. Amphibolite and corundum syenite are rare.

*Dharmapuri anorthosite:* In addition to the several ultramafic intrusions, a linear but irregular NE-trending body of anorthosite occurs near Dharmapuri within the straight belt.

## PROTEROZOIC MAFIC DYKE SWARMS

Dolerite dykes are widespread throughout the craton (Murthy, 1995; Radhakrishna et al. 2004) and belong to two prominent sets trending ENE-WSW and NNW-SSE. While some of them may be broadly contemporaneous, the ENE set appears to be older than the NNE set. The NNE set varies in orientation along a general N-S direction parallel to the trend of schist belts. Despite the wide scatter, concentration of dykes occurs in giant dyke swarms in specific areas, viz., (1) Cuddapah dyke swarm, (2) Tiptur dyke swarm, (3) Hunsur dyke swarm.

*Cuddapah swarm:* They are predominantly dolerite dykes that are quartz and hypersthene normative tholeiites, with subordinate alkalic and transitional types, which are olivine and nepheline normative. Alkalic dykes range from picrite, basanite, tephrite and trachybasalt. The dykes range in length from a few tens of metres up to 400 km and in width from 10 to 50 m, and rarely 80 m. Most dykes have chilled margins, with a coarse-grained core that is at places granophyric. Most dykes, with rare exceptions, terminate against the boundary of Cuddapah basin, indicating that they are older. They may be precursors to the basin formation during doming up of the underlying crust, followed by later subsidence leading to sedimentation. The dykes are invariably enriched in REE, resulting either from magma contaminated with sialic crust or originating from enriched mantle sources. The age of the dykes shows a wide range, representing several pulses of activity. The oldest dykes dated near Mahabubnagar have Sm-Nd whole rock-mineral isochron ages of 2170-2190 Ma. A large swarm of ~2400 Ma is reported from EDC. Rb-Sr, K-Ar and Ar-Ar dates cluster around two large spreads of 1600-1900 Ma and 1100-1500 Ma. Palaeomagnetic studies, coupled with reconnaissance dating in the greenstone and granulite terrain of Dharwar craton, indicate main events of dyke activity around 2400 Ma and 1900 Ma.

*Tiptur swarm:* An intersecting swarm of dykes of similar orientation is seen around Tiptur, cutting across the Kibbanahalli arm of Chitradurga belt. Two sets of dykes are found, the older amphibolite and epidiorite with well-preserved igneous textures, and the more prominent younger dolerite. Large dolerites near Hole Narasipura have indurated the gneisses at the contact and converted them into granophyres of over a width of about one metre. As the granulite terrain is approached to the west in Coorg, the dolerites and amphibolites become hornblende granulites with well-preserved primary textures, chilled margins and cross-cutting relations with host gneisses. The differentiated Chilur dyke near Malavalli gives Rb-Sr isochron age of ~2400 Ma. Sm-Nd age of 1700 Ma is reported for a dyke in central Karnataka. A very long N-S trending dyke near Kunigal gives Rb-Sr isochron age of 1900 Ma.

*Hunsur swarm:* A prominent NNW trending swarm of pyroxene granulite dykes cuts across the foliation and banding of Peninsular Gneiss containing 'incipient charnockite' patches near Hunsur up to Manjirabad and Somvarpet. The basic granulite dykes have sharp and chilled contacts with the gneisses. Original igneous textures are preserved, but the megacrysts of pyroxenes have broken down into granular aggregates. The dykes are characterised by clouded plagioclase caused by magnetite dust formed at ~500°C during exsolution in deep crust (>10 km) that is appropriate for granulite facies. The age of the swarm is uncertain.

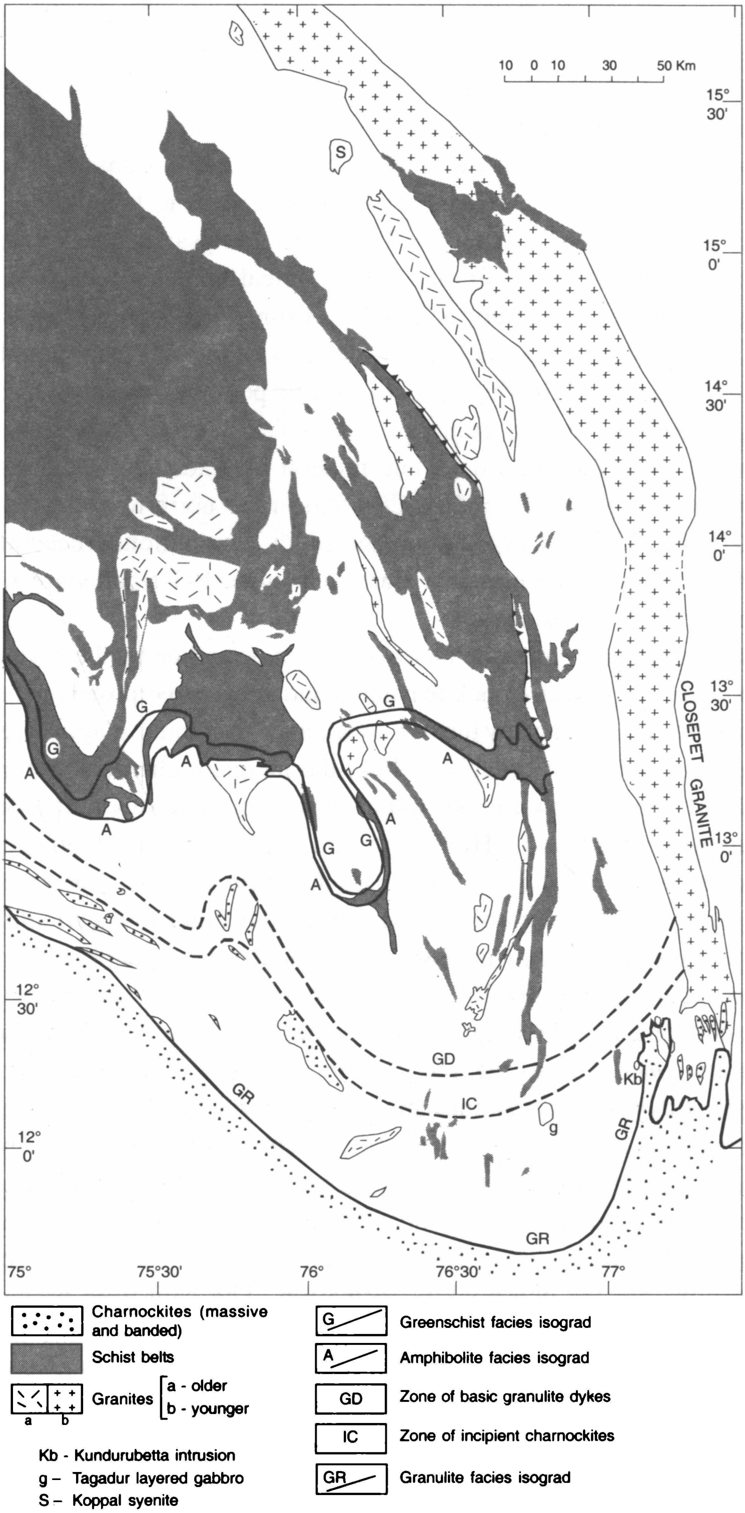
## REGIONAL STRUCTURE

The NNW to NNE trending arcuate 'Dharwar trend' with convexity to the east was earlier conceived as due to superposition of the major northerly trending folds on the older easterly trending recumbent folds. This view did not find much support since the older E-W folds superposed by N-S folds could not be identified on a regional scale. Recent structural studies have shown that N-S trending tight to isoclinal upright folds had been coaxially refolded by a second phase of deformation. The duration of the inter-kinematic interval between the two phases is still a matter of opinion. The two phases are either regarded as discrete events or as the result of single progressive deformation. The third deformational phase produced more open type of folds of lesser intensity. Crustal scale shear zones at the eastern margins of most schist belts are now interpreted as due to sinistral transpression in the late stage of structural evolution. Of late, flower structures (e.g. Bababudan shear zone), strike slip duplexes (e.g., Gadag belt) and tectonic slides (e.g., Sandur and Hutti schist belts) have been recognised in the overall pattern of compressive deformation from the NE. Top-to-SW displacement in Gadag, and the curvature of Nidnegal anticline in Shimoga schist belt confirm the nature of compressive deformation.

There was a unique development in the structural studies of Dharwar craton wherein it was visualised that the Sargur, Dharwar and Peninsular Gneiss (and Dharwar batholith) had similarity of style, sequence and orientation of folding deformation, called by the name of 'structural unity' (Naha et al. 1986). A corollary of this 'structural unity' theory was that the division of schists into an older Sargur and younger Dharwar was untenable and the Peninsular Gneiss, having participated in the deformation of the schists coevally, was younger than the schists. This view overlooked the fact that Peninsular Gneiss, where exposed in areas of less intense regional strain, preserves the original angular unconformable relations with the Dharwar schists. In areas of intense deformation, the Dharwar folds and fabric are superposed on Sargur folds and fabric, resulting in apparent parallelism as a result of rotation of earlier Sargur fabric into parallelism during the younger Dharwar deformation. The gneisses, though involved in both orogenies, were marked by extensive migmatisation in the older Sargur orogeny, but were marked by widespread brittle fractures filled with carbonates in areas of low strain, and by marginal, low grade partial melting in areas close to the crustal scale shear zones. Therefore a critical appraisal of regional field data enables us to distinguish the two stratigraphic groups of older Sargur and younger Dharwar, and their mutual relationships with Peninsular Gneiss, despite the 'structural unity.'

## REGIONAL METAMORPHISM AND CHARNOCKITES

Progressive regional metamorphism from greenschist in the north to granulite facies in the south is well documented in Dharwar craton, and more spectacularly in the WDC (Fig.3D-25), beginning with its first report by B. Rama Rao (1936). The changes in the grade of metamorphism are well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CLOSEPET GRANITE
G
A
GD
IC
GR
Kb
g
Charnockites (massive and banded)
Schist belts
Granites
a - older
b - younger
a
b
Kb - Kundurubetta intrusion
g – Tagadur layered gabbro
S – Koppal syenite
Greenschist facies isograd
Amphibolite facies isograd
Zone of basic granulite dykes
Zone of incipient charnockites
Granulite facies isograd

**Fig.3D-25.** Metamorphic facies in WDC.

documented diagnostically in pelitic and mafic rocks. The pelites contain sericite, chlorite and biotite in greenschist facies, garnet, staurolite and kyanite in amphibolite facies, and garnet, sillimanite and K-felspar in granulite facies. Mafic rocks contain actinolite, chlorite, calcite and albite in greenschist facies, tschermakite, edenite, oligoclase, andesine and almandine in amphibolite facies, and pargasite, hastingsite, hypersthene, salite, andesine, labradorite, pyrope and grossularite in granulite facies. The associated psammitic and carbonate rocks, and BIF also show similar mineralogical changes with progressive metamorphism. Some workers make a finer distinction between granite veining caused by incipient partial melting of the associated gneisses in amphibolite facies, and the partial melting and anatexis of pelites themselves, especially the Mg-Al pelites, during granulite facies. Geothermobarometry, mineral stability and fluid inclusion data, and mineral isograds demonstrate that the P-T conditions graduate from 500°C/ 4-5kb in the north to 600°C/ 5-7kb in the middle and 700-750°C/ 7-8kb in the south. The regional metamorphism of WDC belongs to the classical Barrovian type. P-T-t paths are not well constrained for WDC as a whole.

The amphibolite-granulite facies transition is marked by the development of incipient or arrested charnockite patches and veins, superposed on the fabric of migmatitic gneisses, and by the first appearance of clouded plagioclase dykes. Pichamuthu (1960) first brought to light the incipient charnockite formation (Fig.3D-26) from the now-famous Kabbaldurga stone quarries and the presence of clouded plagioclase in Hunsur dykes. This transition from gneiss to charnockite was also marked by the first appearance of hypersthene and hedenbergite in BIF and garnet-clinopyroxene assemblage in pyribolites.

The transformation of gneisses to charnockites is spectacularly seen in the stone quarries (Fig.3D-26) where charnockite occurs as diffuse greasy patches cutting across the foliation and banding of grey gneisses. At places the patches are concordant to the gneissic fabric or are confined to fractures or selvedges of dykes. The transformation everywhere is marked by hypersthene developing from hornblende in a prograde reaction, and is noticeable in greasy patches and pegmatite veins. The incipient charnockite phenomenon has spawned a wide range of sophisticated laboratory studies by international scientists. These studies led to the conclusion that high-density $CO_2$ inclusions were responsible for charnockite formation. The causative process was debatable, with theories invoking carbonic metamorphism being triggered by the release of carbon dioxide from the mantle or by the breakdown of carbonate sediments. Another popular theory was dehydration melting during anatexis of hydrous minerals like hornblende and biotite present in host rocks. A combination or variation of these hypotheses including the role of hypersaline fluids immiscible with $CO_2$ was also discussed in literature.

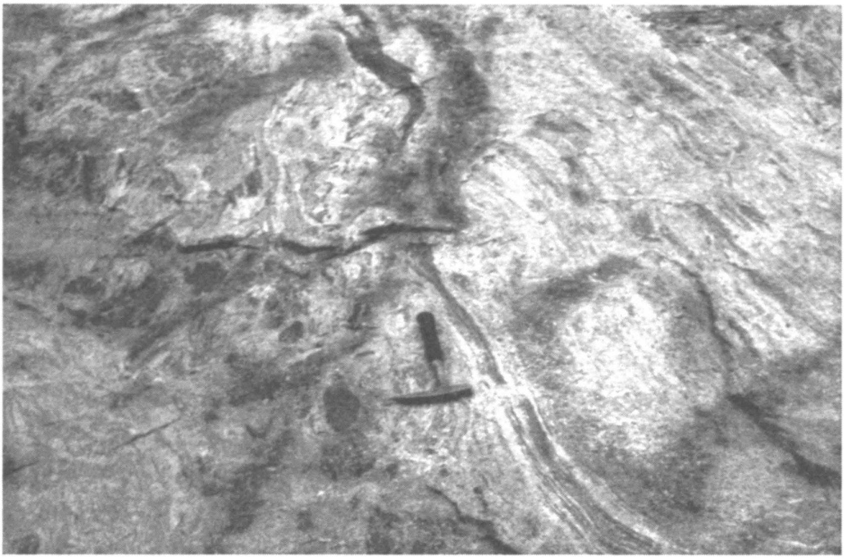


**Fig.3D-26.** Charnockite patches forming in gneiss at Kabbaldurga.

Incipient charnockite development is seen all along the transition zone trending E-W from Mangalore and Coorg in the west to Krishnagiri in the east. The charnockite patches graduate into charnockite massifs, still retaining the N-S Dharwar structural fabrics, although the charnockite belt trends E-W. This feature is the result of the geographical distribution of charnockite belt conforming to regional metamorphic isograds, resulting from the regional northerly tilt of the craton. This gentle tilt of about 2 to5° progressively exposes the palaeo-depth of about 10 km in the north and 25 km in the south. In terms of the present estimates of crustal depths of about 40 km on the average, the burial depth in the granulite belt may be of the order of 60 to 65 km. This has probably resulted mainly through tectonic thickening in WDC and due to the additional factor of heat advection by the batholith in EDC. The slightly shallower depth at which granulite facies metamorphism occurred in EDC through additional heat output is reflected in the northerly shift of the charnockite belt together with the orthopyroxene isograd, extending from the BR Hills to the east in EDC.

The regional metamorphism of EDC occurred on similar lines, but it is of low-pressure facies series with typical pelitic assemblages of andalusite-cordierite-staurolite in amphibolite facies grading into cordierite-garnet-sillimanite-hypersthene in granulite facies, along with lack of garnet in the mafic rocks in amphibolite facies (Buchan type). Metamorphic P-T conditions of EDC range from 670°C / 3kb in Sandur belt in the north, through 710°C / 4-5kb in the middle to 750°C / 6-7kb in Krishnagiri-Dharmapuri area. There is, however, another view that low-pressure metamorphism in granulite facies is not supported by thermobarometric data from Shevaroy and Kollimalai Hills, but this is not consistent with regional metamorphic framework. Closepet Granite follows a similar progressive low-pressure metamorphic pattern from north to south. The low-pressure metamorphism of EDC is caused by the abundance of younger granites providing the advective heat, which was lacking in the WDC.

The Karimnagar granulite belt in the EDC similarly indicates progressive metamorphism of greenschist to lower amphibolite facies from southwest (Ramagiri belt) to upper amphibolite to granulite facies in the northeast (Warangal Group and Karimnagar charnockites). The greenstone belts also narrow down in size and break up into enclaves as the granulite belt is approached, but there is no tectonic dislocation separating them. This is similar to the N-S crustal section described earlier from WDC, and clearly brings out the oblique crustal zonation towards the granulite boundary to the south and northeast. It is therefore not unlikely that the depth profile anywhere in the craton may be of similar configuration with charnockites underlying the quartzo-feldspathic gneisses and granites.

## GEOPHYSICAL STUDIES

Insight has been gained into the deep continental structure of Dharwar craton through regional gravity and magnetic surveys (Singh et al. 2004). Deep seismic sounding (DSS) studies along the E-W trending Kavali-Udupi profile (Fig.3D-27a, b) drawn across the regional grain of the craton provided valuable information, which was synthesised as the first geotransect in India (Radhakrishna and Ramakrishnan, 1993). The gravity anomalies over the craton have a total relief of 80 mGal ranging from –50 mGal near Mangalore to –130 mGal near Kuduremukh and Mercara (Madikeri). The gravity contours show striking correlation with regional structural trends. The schist belts show positive anomalies of 10 to 30 mGal and the gneisses are marked by gravity lows. Gravity modelling suggests that Bababudan-Shimoga-Goa belt is a shallow basin with a depth of 3 to 4 km, whereas Chitradurga and Sandur belts are narrow and deep (>10 km), that is suggestive of rifts.

Aeromagnetic anomalies show a striking change from the N-S strike of the craton to E-W trends in SGT. Schist belts rich in BIF show strong bipolar anomalies. Magnetic highs are pronounced in the charnockitic terrain of SGT. Concealed schist belts (Aladahalli), layered basic intrusion (Thagaduru) and large ENE trending basic dyke of cratonic extent near Mysore are identified from aeromagnetic data. Schist belt configuration and dyke trends are refined from this information, in conjunction with satellite remote sensing data.

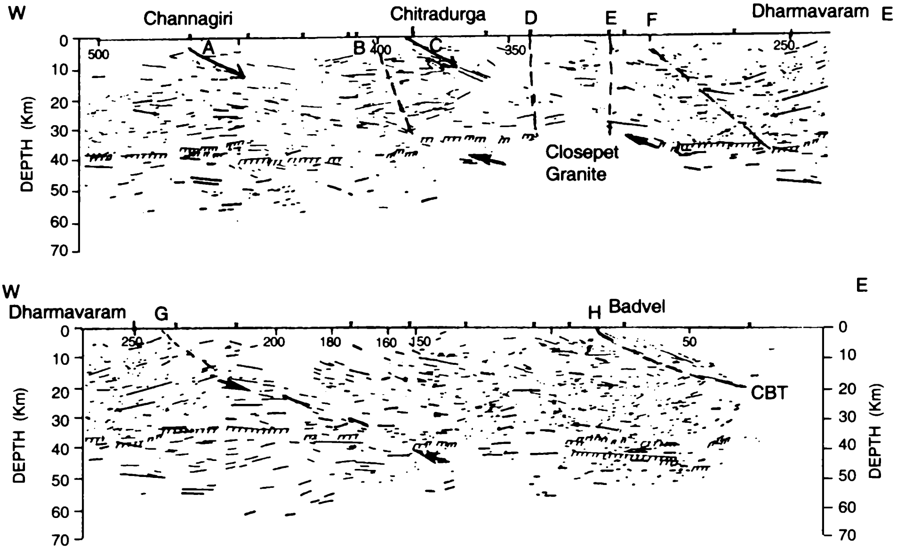


**Fig.3D-27a&b.** Simplified DSS profile from near Chennagiri to Badvel forming part of Udupi-Kavali profile after Kaila et al. (1979) as modified by Gibbs (1986). **A** - Low angle fault at the eastern margin of Shimoga schist belt near Chennagiri. **B** - Steep fault at the Western margin of Chitradurga schist belt defining depositional boundary (?). **C** - Chitradurga boundary fault between WDC and EDC. **D** & **E** - Boundaries of Closepet Granite. **F** - Moderately dipping fault at the margin of Sandur belt. **G** - Low-angle fault defining the shear zone near Jonnagiri-Kadiri belt and the western margin of Cuddapah basin. **H** - Cuddapah boundary thrust near Badvel. (Courtesy: American Geophysical Union).

The DSS profile reveals several parallel mantle deep vertical faults, some of which may relate to Dharwar rift basins. More important are the east-dipping imbricate thrusts coinciding with the boundary shear zones of Shimoga and Chitradurga belts, and the Cuddapah boundary thrust. Moho depth is shown to vary from 38 to 41 km in WDC to 34 to 38 km in EDC. This is corroborated by teleseismic tomography and receiver function analysis of broad band seismograms, as well as by magneto-telluric studies along the transect from Raichur to Goa. Low upper mantle velocity patterns in WDC, as compared to higher values in EDC, are also suggested.

Deep seismic reflection and combined refraction-wide angle reflection profile from Kuppam near Kolar to MBASZ in EDC (*see* Ramakrishnan, 2003a) has brought out a four-layered crustal velocity structure, with a low velocity zone (7-15 km thick) at mid-crustal levels. Crustal thickness varies from 41 to 45 km along the profile. Moho upwarp is noticed near Nagarasampatti in the Dharmapuri (Tirupathur) alkaline province. Opposing reflectors dipping north and south may suggest the presence of Dharmapuri rift.

## TECTONIC EVOLUTION

With the advent of plate tectonics in the sixties, geosynclinal models became passé, but Precambrian geologists viewed the new theory with circumspection. The debate in the Dharwar craton was centred on whether the greenstone belts had sialic or simatic basement. Once it was realised that modified angular unconformities marked by basal conglomerates (QPC) were extensive in the main schist belts, it became firmly established that their basement was sialic. Continental rifting models became popular, but they had to contend with the oceanic basalts identified geochemically within the schist belts. The identification of two tectonic blocks viz., the WDC and EDC separated by Closepet Granite suggested the idea that the granite may mark a 'geosuture'. This idea is being followed even now in a few new tectonic models.

One of the popular models (S.A. Drury, R.C. Newton) is that the greenstone belts are back-arc marginal basins separated from Andean arc or Cordillera at the southern margin of the Dharwar craton adjacent to the E-W trending and north-verging subduction zones, now marked by crustal scale shear zones. The greenstone/schist belts were conceived as E-W trending depositories, which were tectonically modified within the ubiquitous N-S trending shear systems that produced the current N-S configuration of schist belts (Newton, 1990). A modification to this model (S.M. Naqvi, C. Manikyamba) is that the greenstone belts are sited over mantle plumes emanating from shallow subduction zones, thus producing the N-S configuration. Kolar and Ramagiri schist belts in EDC were visualised in some models as suture zones between two continental blocks, which came together around 2500 Ma. Komatiites and tholeiites of schist belts together with calc-alkaline gneisses intruding them were later regarded as Archaean examples of arc accretion (E.J. Krogstad, G.N. Hanson, V. Rajamani). A variation of island arc model is that the subduction zone trending E-W is located in the north, buried beneath Deccan Trap. This model is based on the visualisation that the original Dharwar basins extended E-W and modified to NNW trend by later deformation (R. Srinivasan, K. Naha). A modified tectonic model was also proposed recently involving the non-uniformitarian 'sagduction', a process involving gravitational sinking of greenstone pile into the gneissic basement together with tectonic slides at the margins (D. Chardon, J-J. Peucat, M. Jayananda), but this model has not accounted for the large-scale, top-to-southwest overthrusts described from many schist belts.

In yet another elaborate model of convergent model evolution (Chadwick et al. 2000) like the Andes and East Indies (Fig.3D-28 a & b), the WDC was regarded as the foreland having schist belts as marginal basins. The EDC was interpreted as an Archaean batholith (called Dharwar batholith) that accreted

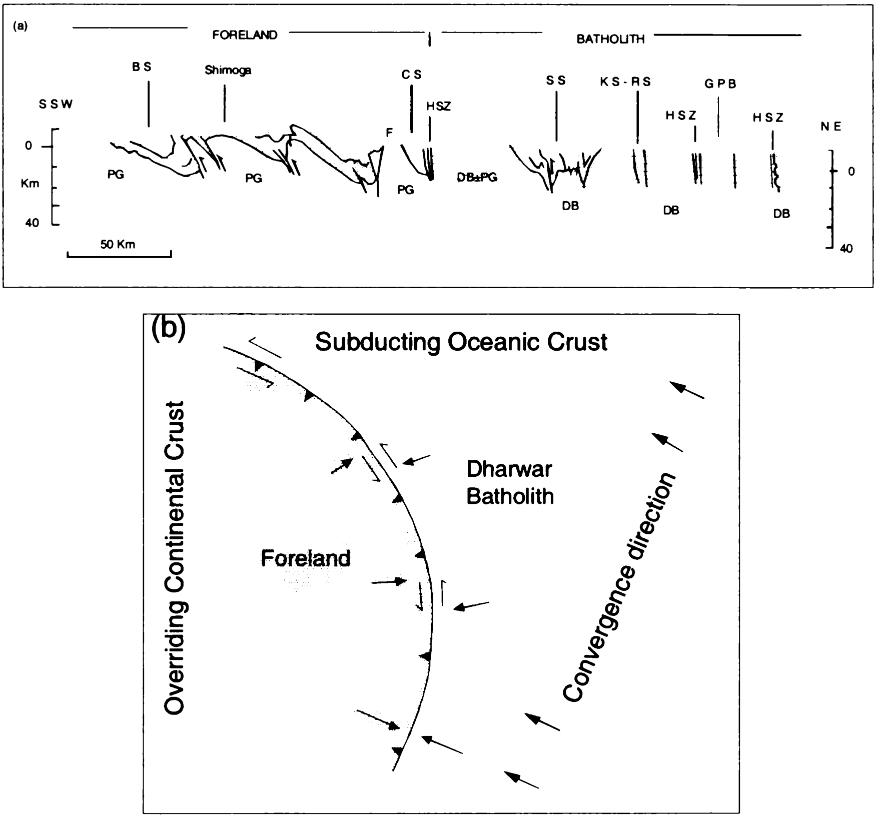

(a)
FORELAND
BATHOLITH
SSW
BS
Shimoga
CS
HSZ
F
SS
KS-RS
GPB
HSZ
HSZ
NE
0
Km
40
PG
PG
PG
DB±PG
DB
DB
DB
0
40
50 Km
(b)
Subducting Oceanic Crust
Overriding Continental Crust
Dharwar Batholith
Foreland
Convergence direction

**Fig.3D-28.** Arc accretion model of Dharwar craton (after Chadwick et al. 1999, 2000). (**a**) Cross section. (**b**) Convergence direction. BS - Bababudan schist belt. CS - Chitradurga schist belt. SS - Sandur schist belt. KS-RS - Ramagiri-Hungund schist belt. GPB - Plutonic belt of granodiorite. PG - Peninsular Gneiss basement to the Dharwar Supergroup. DB - Dharwar Batholith. HSZ - High strain zone. F - Fault.

on to the craton around 2750-2510 Ma, with the Eastern greenstone belts developing as intra-arc basins. The NE to SW shortening as a result of arc-normal compression has resulted in the sinistral transpressive shear systems at the margins of most schist belts. The oblique convergence of an oceanic plate that was subducting towards WNW resulted in the Archaean plate tectonic evolution of Dharwar craton. Closepet Granite, until recently regarded as a unique meridional intrusion between the EDC and WDC, was considered as part of the Dharwar batholith, consisting of many such parallel plutonic belts. While providing a holistic picture explaining the dominant features of the craton, the model has to contend with the absence of fore arc accretionary prism in the east and missing sutures marked by dismembered ophiolites and mélange. It has also to account for the marginal marine, albeit thin, stable continental sediments along the western margin of most of the

Eastern greenstone belts, the wide occurrence of quartzite-carbonate suite in the older Warangal Group that grades into the Karimnagar granulite belt, and isotopic ages >3 Ga from many areas in EDC.

The evolution of the schist belts as continental rifts, which opened up to form small ocean basins that closed by compression from NE towards SW may explain these anomalies (Ramakrishnan, 1987a). The preferred model (M. Ramakrishnan) is that the batholithic terrain in the east may have evolved on a thin continental crust as a continental margin arc that resulted from basaltic underplating, followed by plume activity in the EDC. Geochemical data suggest that the greenstone volcanics are not the substantial sources for the surrounding granites and this favours both underplating intra-arc models. Granitic magmatism was concurrent with the development of felsic volcanics, pyroclastic rocks and polymict granite-clast volcanic conglomerates (Champion Gneiss). The granitic terrain was rapidly unroofed, contributing clasts to the Palkanmaradi and similar conglomerates. Intense deformation resulted in sinistrally sheared and mylonitised margins of most schist belts of EDC, and culminated in the closure of the basins. Batholith emplacement caused the ubiquitous low P/high T metamorphism in the EDC. In the WDC, on the other hand, the basins closed by thrusting of the distal gneissic basement on to the foreland, with the contact zones here also marked by sinistral shearing and intense mylonitisation. There was no significant plume activity and the heat was largely conductive, producing intermediate pressure metamorphism on a cooler sialic crust. The exhumation of the craton in the Proterozoic, together with crustal tilting, unroofed the granulite terrains with the transition zones in the south, east and northeast, producing excellent oblique crustal cross-sections.

# BASTAR CRATON

## INTRODUCTION

Bastar Craton covers an area of 1,30,000 km$^2$ and is bounded by the Godavari graben in the south, Mahanadi graben in the north-east, Central Indian Tectonic Zone (CITZ) forming part of the Satpura mobile belt in the north, Eastern Ghats mobile belt in the east and Deccan Trap cover in the west (Fig.3B-1). Bastar craton has also been referred to in literature as Bhandara craton or Central Indian craton.

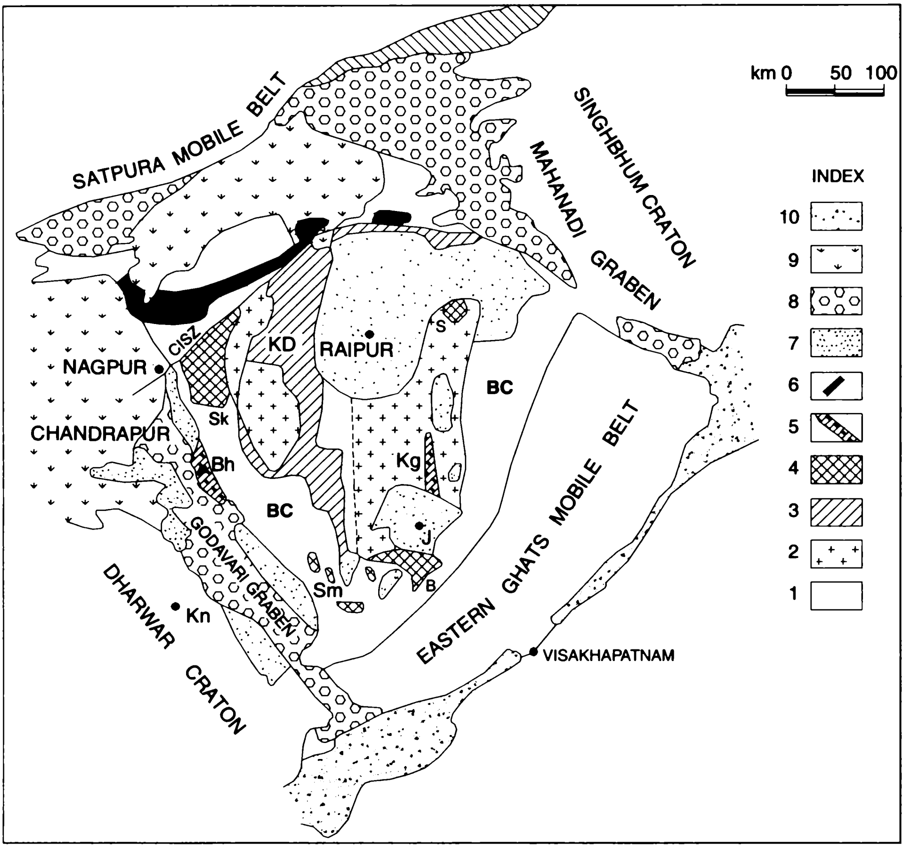
### Main Components:

The important lithotectonic associations in the craton are (Fig.3B-2):

1. Gneissic Complex (Sukma, Amgaon), with granites of different ages (Dongargarh, Malanjkhand, Kanker, Jhiram, Sukma etc.)
2. Granulite belts (Bhopalpatnam, Kondagaon)
3. Kotri-Dongargarh orogen
4. Isolated fold belts of Bengpal, Sakoli and Sonakhan
5. Mafic dyke swarms (Bijapur, Gidam, Kondagaon, Keshkal)
6. Proterozoic 'Purana' basins (Abujhmar, Chhattisgarh, Khariar, Indravati, Pranhita-Godavari etc)

A broad description of these litho-tectonic units is given below:

(1) *Gneissic Complex* consists essentially of TTG (tonalite-trondhjemite-granodiorite) suites that are extensively exposed in the south and west of the craton. The gneisses yield widespread ages of 2500-2600 Ma signifying a major crustal accretion event, along with some ages of ~3000 Ma. Vestiges of older events are recorded by U-Pb zircon ages (Ghosh, 2004) of 3510 Ma (Markampara gneiss in south Bastar) and 3560 Ma (Kapsi gneiss in central Bastar). The TTG gneisses enclose rafts of 'continental' sediments of quartzite-carbonate-pelite (QCP) facies, together with minor BIF and mafic-ultramafic rocks (e.g., Sukma Group of Bastar and Amgaon Group of Bhandara). Large bodies of younger granites intruding the gneisses and supracrustals are conspicuous entities in the craton. Dongargarh granite intruding the Kotri-Dongargarh orogen is closely associated with felsic volcanics. Malanjkhand


SATPURA MOBILE BELT
SINGHBHUM CRATON
MAHANADI GRABEN
NAGPUR
CHANDRAPUR
CISZ
KD
RAIPUR
S
Sk
BC
Bh
Kg
J
Sm
B
GODAVARI GRABEN
DHARWAR CRATON
Kn
EASTERN GHATS MOBILE BELT
VISAKHAPATNAM
km 0 50 100
INDEX
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6
5
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3
2
1

**Fig.3B-1.** Disposition of Bastar craton (BC) surrounded by other cratons, mobile belts and graben. *Index:* **1** - Unclassified gneisses and granites. **2** - Younger granites. **3** - Kotri-Dongargarh orogen (KD). **4** - Isolated supracrustal belts (Sk - Sakoli, B - Bengpal, S - Sonakhan, Sm - Sukma). **5** - Granulite belts (Bh - Bhopalpatnam, Kg - Kondagaon). **6** - Sausar belt. CISZ - Central Indian Shear Zone. **7** - 'Purana' basins (Mesoproterozoic). **8** - Gondwana basin (Permocarboniferous to Cretaceous). **9** - Deccan Trap (C-T boundary). **10** - Alluvium. **J** - Jagdalpur, **Kn** - Karimnagar (after Ramakrishnan, 1990).

granite that is contemporaneous with Dongargarh granite is responsible for the famous Malanjkhand copper deposit of 'porphyry type (?)'. The widespread Kanker granite forms the basement to the 'Purana' basins of Bastar craton. Jhiram granite is host to deposits of tin, lepidolite mica and pegmatitic minerals. Sukma granite underlies the Sabari 'Purana' basin.

(2) *Granulites* including charnockites, leptynites and high-grade supracrustal enclaves occur as two prominent belts in the craton, viz., (1) Bhopalpatnam granulite belt forming the northern shoulder of Godavari graben that conceals the actual contact between the Dharwar and Bastar cratons,

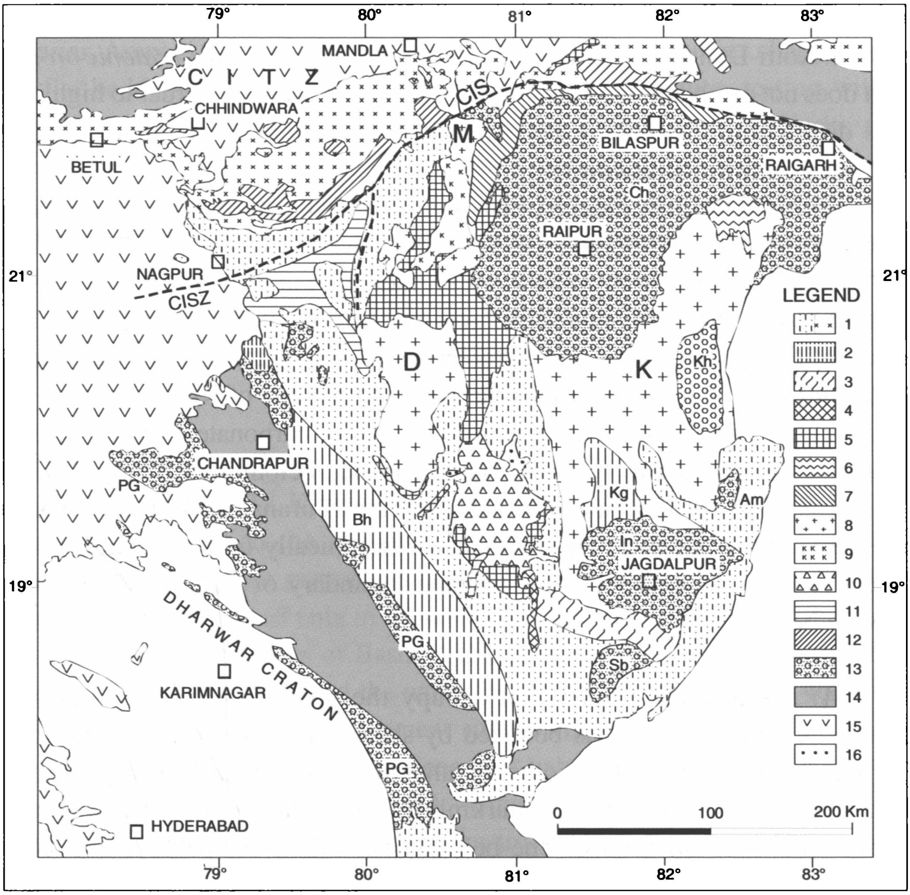

79°
80°
81°
82°
83°
21°
19°
MANDLA
C I T Z
CHHINDWARA
CIS
M
BILASPUR
RAIGARH
BETUL
Ch
RAIPUR
NAGPUR
CISZ
LEGEND
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
D
K
Kh
CHANDRAPUR
PG
Kg
Am
Bh
In
JAGDALPUR
DHARWAR CRATON
PG
Sb
KARIMNAGAR
PG
0
100
200 Km
HYDERABAD

**Fig.3B-2.** Lithotectonic elements of Bastar craton. **1** - (a) Gneissic complex with Sukma and Amgaon enclaves; (b) Unclassified granites and gneisses. **2** - Granulite belts (Kg - Kondagaon, Bp - Bhopalpatnam). **3** - Bengpal belt. **4** - Bailadila Group. **5** - Nandgaon Group. **6** - Sonakhan Group. **7** - Chilpi Group. **8** - Granites (D - Dongargarh; K - Kanker; M - Malanjkhand). **9** - Khairagarh Group. **10** - Abujhmar Group. **11** - Sakoli Group. **12** - Sausar Group. **13** - 'Purana' basins (Ch - Chhattisgarh; Kh - Khariar; Am - Ampani; In - Indravati; Sb - Sabari; P-G - Pranhita- Godavari). **14** - Gondwana basin. **15** - Deccan Trap. 16 - Alluvium (after Ramachandra et al. 2001). CISZ - Central Indian Shear Zone.

and (2) Kondagaon granulite belt that emerges from under the northern margin of Indravati 'Purana' basin in the cratonic interior. The third granulite belt called Balaghat-Bhandara granulite belt forms part of the CITZ at the cratonic boundary, and is described under Satpura mobile belt.

(3) *Kotri-Dongargarh Orogen* is a long, N-S trending belt consisting of several cycles of sedimentation and volcanism that progressively becomes younger towards north. These supracrustal cycles are limited to the geographical

confines of the linear belt, and do not extend far in to the surrounding gneissic terrain. Kotri-Dongargarh belt is therefore described as an *intra-cratonic orogen* that does not extend beyond the boundary of Bastar craton. In order to highlight this distinction, this belt is not called here as a *mobile belt* which usually surrounds individual craton(s).

Kotri-Dongargarh orogen consists of several volcano-sedimentary cycles, which are in the ascending order: (i) basic volcanics-fine clastics-BIF association of Bailadila Group (rich in iron ores) unconformably deposited over the gneissic basement that contains enclaves and belts of older supracrustal rocks, (ii) Mafic-felsic volcanics and pyroclastics of Nandgaon Group, (iii) Mafic volcanics alternating with clastics (arenites and pelites) of Khairagarh Group, and (iv) Greywacke-pelite association with minor carbonates, cherts (locally manganese bearing) and volcanics (largely felsic), belonging to Chilpi Group. The orogen is overlain unconformably by the 'Purana' sedimentary basins (Chhattisgarh, Abujhmar) and is truncated tectonically by the Central Indian Shear Zone (CIS) that marks the southern boundary of CITZ or the Satpura mobile belt.

(4) *Isolated Fold Belts* that occupy the gneissic terrain are: (i) the triangular Sakoli belt that is bounded by shear zones on all three sides, one parallel to CIS in the north, another parallel to Kotri-Dongargarh orogen in the east and possibly yet another marking the southern boundary that trends parallel to Godavari graben. The belt consists mainly of pelites with felsic volcanics and pyroclastics, minor mafic-ultramafic rocks, meta-exhalites (tourmalinites, coticules, BIF etc) and Sedex-type Cu-Zn and gold-scheelite mineralisation. The lithological ensemble is *broadly* comparable with Chilpi Group. (ii) Sonakhan belt is described as a 'greenstone belt' consisting mainly of pillowed basic volcanics and tuffs, overlain by a thick conglomerate-sandstone formation. The belt is unconformably overlain by the Chhattisgarh 'Purana' basin and is correlatable with Nandgaon Group. (iii) Bengpal belt is WNW-ESE trending fold belt extending from the east of Bailadila hills up to the marginal zone of Eastern Ghats mobile belt, and consists essentially of amygdular basalt-andalusite phyllite-arenite association. The belt is bounded by Sukma gneisses and Bengpal granites, and by the Indravati and Sabari basins. Bengpal Group underlies the Bailadila Group of Kotri-Dongargarh belt.

(5) *Mafic Dyke Swarms* form prominent clusters near Bijapur, Gidam, Kondagaon and Keshkal. They are chiefly amphibolites, epidiorites and dolerites of variable composition, and are emplaced predominantly in a NW direction.

(6) *Proterozoic 'Purana' Basins* are mainly the Abujhmar, Chhattisgarh, Khariar, Ampani, Indravati, Sabari and Pranhita-Godavari basins characterised by flat-bedded sequences of quartzite-carbonate-pelite suite, resting with a profound unconformity on the Precambrian basement of gneisses and granites along with their supracrustal belts and enclaves. These basins are surrounded by smaller outliers (known by various local names) thereby strongly suggesting that the 'Purana' sediments were deposited in a large, once-continuous basin on an undulating topography with interlinking channel ways. These basins are described in the chapter on Proterozoic Sedimentary Basins.

## Previous Studies

V. Ball in 1877, W. King in 1881-86 and P.N. Bose in 1899-1900 were the pioneers who studied the geology of northern Bastar. H.Crookshank and P.K.Ghosh mapped the geology of southern Bastar during 1932-38, but their work could be published only in the sixties (Crookshank, 1963). Ghosh (1941) described the charnockites of Bastar. S.N. Sarkar studied the Dongargarh belt during 1957-58 and proposed the name Dongargarh System for the volcanics and sediments of the belt. Lineament studies (Bhate, 1980) brought out the importance of N-S trending Kotri lineament named after Kotri River in north Bastar. The volcano-sedimentary belt within the lineament was called Kotri Supergroup, which is merely the southward strike extension of Dongargarh Supergroup of S.N. Sarkar (Mishra et al. 1988). The whole belt therefore has come to be known as Kotri-Dongargarh belt. Recent geological summaries of Bastar craton are available in Chatterjee (1970), Mishra et al. (1988), Ramakrishnan (1990), Bandyopadhyay et al. (1995), A. Roy et al. (2000), Ramachandra et al. (2001), Basu (2001) and Ramachandra (2004). Geol. Soc. India Mem. No.6 (1987); and reviews by Das et al. (2001) and Chaudhuri et al. (2002) give detailed accounts of the 'Purana' basins of Bastar craton. Younger granites of the craton are described by Ramachandra and Roy (1998). Ramachandra et al. (1995), Subba Rao et al. (2003) and Srivastava and Singh (2004) describe the dyke swarms of Bastar craton. Srivastava et al. (2004) and Srivastava (2006) describe the geochemistry of mafic volcanics of Bastar. Neogi et al. (1996) and Sensarma et al. (2002) describe the geochemistry of Dongargarh volcanics. Geochronological data for the craton are summarised by A. Sarkar et al. (1990) and G. Sarkar et al. (1993). Special publications dealing with various geological aspects of the craton are the following: GSI (1981, 1990, 2000a), Geol. Soc. India Mem.No.31 (1995) on "Continental Crust of Northwestern and Central India" and Gondwana Geol. Mag. Spl. Vol.7 (2003) on "Advances in Precambrian of Central India".

## REGIONAL STRATIGRAPHY

The regional stratigraphic scheme applicable to Bastar craton, including Kotri-Dongargarh orogen, is given in Table 3B-1.

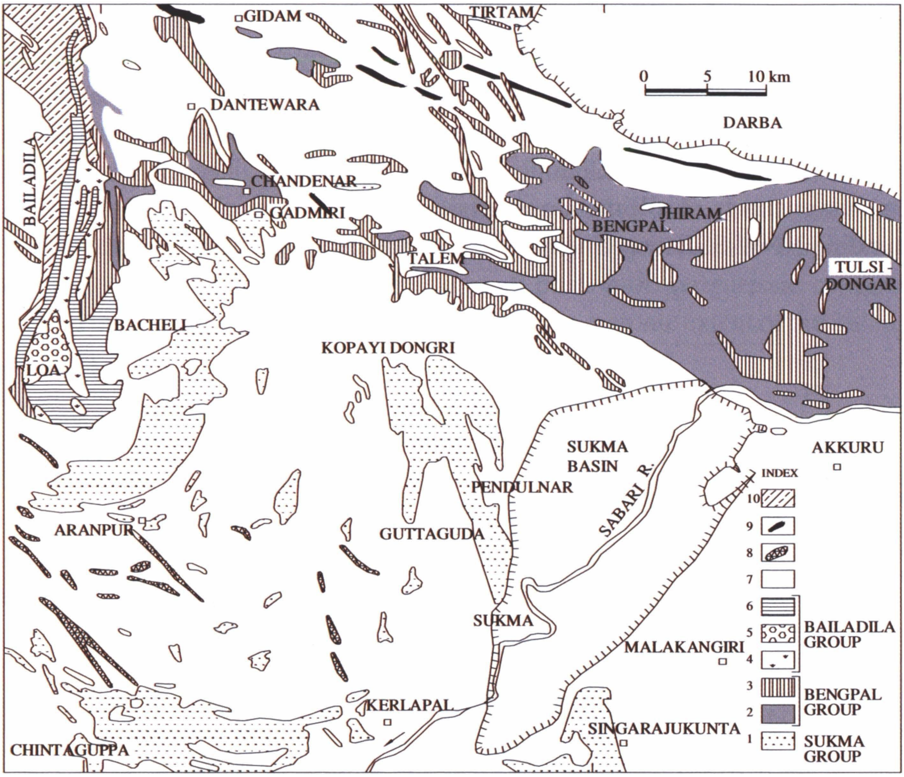
**Table 3B-1.** Generalised stratigraphy of Bastar craton

| Kotri-Dongargarh Orogen | | Rest of the craton | |
|---|---|---|---|
| 1800–2000 Ma | Chilpi Group | 1800–2000 Ma | Chilpi Group = Sakoli Group |
| ~2200 Ma | Khairagarh Group | | |
| ~2300 | Dongargarh Granite | ~2300 | Malanjkhand Granite<br>Kanker Granite |
| ~2300 Ma | Nandgaon Group | 2300 Ma | Sonakhan Group |
| ~2400 Ma | Bailadila Group | | |
| 2500–2600 Ma | Bengpal Group | 2500–2600 Ma | Bengpal Group |
| | | 2600 Ma | Bhopalpatnam and Kondagaon granulites, Sukma granites |
| ~3000 Ma | Amgaon Group | ~3000 Ma | Sukma Group |
| > 3000 Ma | Gneissic Complex with vestiges of 3500-3600 Ma events | | |

*Stratigraphic Problems*

1. The oldest supracrustal suites recognized in Bastar craton are found in southern Bastar. There are two groups of old supracrustals in southern Bastar, namely Sukma Group and Bengpal Group (Fig.3B-3) H.Crookshank and P.K.Ghosh who did pioneering work in the terrain during 1932-38, differed fundamentally in stratigraphic perception. Crookshank divided the supracrustals into Sukma and Bengpal 'Series', but Ghosh held the view that all the supracrustals were facies variants of one group and therefore proposed a composite stratigraphy for Bengpal 'Series' (*see* Crookshank, 1963). Most subsequent workers favoured the view of Ghosh and all the old supracrustals are described even in recent literature under Bengpal Group.

The division of Crookshank was based on the distinction of different lithological associations for each group. Sukma Group has the characteristic lithology of sillimanite quartzite, diopside-rich calc-silicate rocks and cordierite-sillimanite gneisses, cordierite-anthophyllite rocks and BIF. Bengpal Group has the characteristic lithology of amygdular metabasalts intercalated with andalusite (chiastolite) schists and subordinate quartzites. Sukma Group is scattered as swathes and enclaves within gneisses, whereas Bengpal Group occurs in a disjointed WNW-ESE trending belt, flaring to the east. The disjointed


GIDAM
TIRTAM
DANTEWARA
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DARBA
BAILADILA
CHANDENAR
GADMIRI
JHIRAM
BENGPAL
TALEM
TULSI-DONGAR
BACHELI
LOA
KOPAYI DONGRI
SUKMA BASIN
SABARI R.
AKKURU
INDEX
PENDULNAR
ARANPUR
GUTTAGUDA
10
9
8
7
6
5
4
BAILADILA GROUP
3
2
BENGPAL GROUP
1
SUKMA GROUP
SUKMA
MALAKANGIRI
KERLAPAL
SINGARAJUKUNTA
CHINTAGUPPA

**Fig.3B-3.** Geological map of southern Bastar (after Crookshank, 1963). **1** - Sukma Group. **2** - Andalusite schists and quartzites. **3** - Amygdular metabasalts intercalated with andalusite schits and quartzites. **4** - Quartzites and chlorite phyllites. **5** - Loa conglomerate. **6** - Banded Iron Formation. **7** - Unclassified gneisses and granites. **8** - Basic dykes (amphibolites). **9** - Quartz veins marking shear zones. **10** - Laterites.

nature of the belt is due to profuse invasion by younger granites. The intervening basement gneisses and intrusive granites within the Bengpal belt contain numerous enclaves of Sukma Group, which gave an erroneous impression that they may form part of Bengpal Group since they occur within the geographic confines of Bengpal belt and show the same low-pressure metamorphism (andalusite-sillimanite type) as the Bengpal Group. There is, however, a significant difference in that Sukma Group is usually metamorphosed under upper amphibolite and granulite facies, whereas the associated Bengpal Group shows greenschist to lower amphibolite facies. Exceptionally however, where intrusive granites with their pegmatitic-hydrothermal phases intrude Bengpal Group as in Jhiram valley, the pelites are felspathised and become enriched in fibrolite nodules, and greenish grey basalts become nearly black amphibolites. Sukma and Bengpal Groups therefore form separate entities in terms of lithological ensemble, distribution in space and metamorphic impress, save for exceptional situations, and do not constitute a composite Bengpal Group belonging to a single orogenic cycle as described by Misra et al. (1988).

A major evidence for separation of Sukma and Bengpal Groups into two different orogenic cycles is the presence of angular unconformity between Sukma and Bengpal in Chandenar basin (Fig.3B-4). The closely spaced Sukma enclaves of sillimanite quartzite-calc silicate rock-cordierite gneiss trending NNW-SSE near Gadmiri are abruptly truncated by the metabasalts of Bengpal Group trending E-W at Pesal Dongri and Epiya Dongri hills. Those who believed in the composite Bengpal Group visualised this unconformity as between the older Bengpal and a newly visualised, younger Chandenar sequence. But the regional correlation of Chandenar basin with the type area of Bengpal is too compelling to admit the visualisation of a new younger sequence in Chandenar basin. Another regional discordance between the Sukma swathe north of Gariapal (Kopayi Dongri) and the Bengpal belt at Talem (Fig.3B-3) confirms the Sukma-Bengpal orogenic separation.

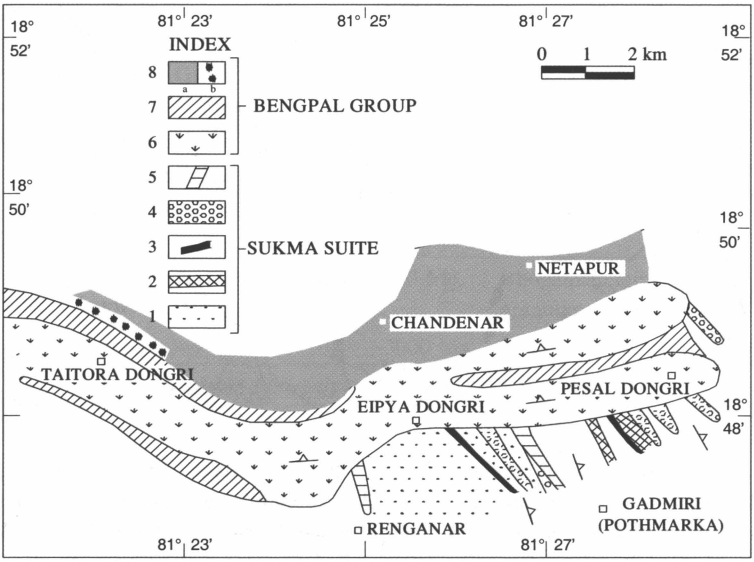

18° 52'
81° 23'
81° 25'
81° 27'
18° 52'
INDEX
8
a
b
7
6
5
4
3
2
1
BENGPAL GROUP
SUKMA SUITE
0 1 2 km
18° 50'
18° 50'
NETAPUR
CHANDENAR
TAITORA DONGRI
EIPYA DONGRI
PESAL DONGRI
18° 48'
GADMIRI
(POTHMARKA)
RENGANAR
81° 23'
81° 27'

**Fig.3B-4.** Angular unconformity between Sukma and Bengpal Groups at Chandenar. **1** - Quartzite. **2** - Calc-silicate rocks. **3** - Amphibolite. **4** - Cordierite gneiss. **5** - Banded Iron Formation. **6** - Metabasalts. **7** - Andalusite schist. **8a** - Andalusite quartzite. **8b** - Conglomerate (after Ramakrishnan, 1990).

2. S.N. Sarkar in 1957-58 called the old supracrustal sequence around Bhandara as Amgaon Group that occurs as scattered enclaves in Amgaon Gneiss. The enclaves are mainly quartzites, garnet-staurolite-kyanite-sillimanite

schists, cordierite-anthophyllite rocks, amphibolites and chromiferous ultramafic rocks, with subordinate calc-silicate rocks and marbles. There is a view that some of these enclaves may form part of the Sakoli belt, separated by deformation and metamorphism from the main belt across shear zones. Although the Amgaon Group is broadly correlatable with Sukma Group, the lithological assemblages do not show one-to-one correlation. Moreover, the Amgaon and Sukma enclaves are not established by mapping as geologically contiguous. Further, Amgaon Gneiss forms only a small portion of the gneissic complex around the Sakoli belt, in comparison with the vast cratonic extent of the Sukma gneisses.

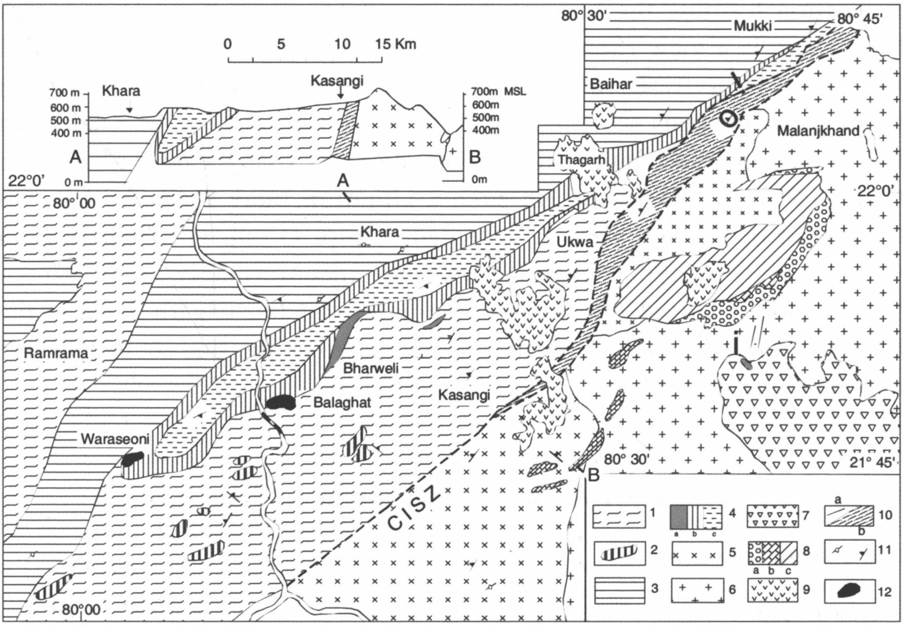

0 5 10 15 Km
700 m
600 m
500 m
400 m
0 m
Khara
Kasangi
A
B
700m MSL
600m
500m
400m
0m
22°0'
80°00
80°30'
Mukki
80° 45'
Baihar
Malanjkhand
Thagarh
22°0'
A
Khara
Ukwa
Ramrama
Bharweli
Balaghat
Kasangi
Waraseoni
CISZ
80° 30'
21° 45'
B
80°00
1
2
3
4
a b c
5
6
7
8
a b c
9
10
a
b
11
12

**Fig.3B-5.** Geological map of Bharweli-Ukwa belt. **1** - Tirodi Gneiss. **2** - Two-pyroxene granulite. **3** - Sausar Group. **4** - Bharweli Group - Basal grit (a), sericite-chlorite schist/phyllite (b) and sericitic phyllite (c), **5** - Amgaon Gneiss. **6** - Malanjkhand Granite with gabbro dykes and quartz veins. **7** - Nandagaon Group. **8** - Chilpi Group - Basal grit-conglomerate (a), crystalline limestone (b), phyllite (b). **9** - Deccan basalt and laterite. **10** - The CISZ (a), phyllonites of the CISZ (b). **11** - Attitude of bedding/foliation. **12** - Manganese ore. Vertical section across A-B is shown in the inset (after Jain et al. 1990).

3. The stratigraphic status of Chilpi Group (Fig.3B-2) is problematic. The Chilpi Beds of W. King and Chilpi Ghat Series of P.N. Bose were later designated as Chilpi Group (GSI, 1981), as best exposed in the Chilpi Ghat and Malanjkhand areas. R.C. Burton in 1912-14 classified the schists of Bharweli-Ukwa area as the older Sonewani 'Series' and younger Chilpi

Ghat 'Series', separated by an unconformity. Since then the 'Manganese Party' of Geological Survey of India (Narayanaswami et al. 1963) suggested that Chilpi Ghat rocks may be low-grade extensions of Sausar Group or may belong to a still a younger group. Jain et al. (1990) suggested that the low-grade rocks of Bharweli-Ukwa area in the Baihar-Balaghat region (Fig.3B-5) belonged to a separate Bharweli Group that was younger than the Sausar Group. Bharweli Group occurs to the north of CIS, whereas Chilpi Group occurs to the south, although they come close to each other in Malanjkhand area with a tenuous link across the CIS, and therefore their stratigraphic correlation is not straightforward. Chilpi rocks are regarded by some others either as continuous with or as a facies variant of Bortalao Formation forming the base of Khairagarh Group in Kotri-Dongargarh belt. There is a view (Sensarma and Mukhopadhyay, 2003) that Bortalao Formation is divisible into two units, one unit (Chandsuraj Formation) forming a continuous succession with the overlying volcanics of Khairagarh Group, and the other unit (Bijepar Formation) as younger than Khairagarh Group. Bijepar Formation, in such a situation, may form the base of Chilpi Group. If this view is accepted, Chilpi Group may constitute a younger unit overlying Khairagarh Group unconformably within Kotri-Dongargarh belt. It also extends to the north of Chhattisgarh basin in the Bilaspur-Raigarh belt, where it is separated from the Sausar belt by the mylonitic gneisses of CIS..

## DESCRIPTION OF STRATIGRAPHIC DIVISIONS

### Older Supracrustals

#### Sukma Group

Large swathes and widespread enclaves of supracrustals within the TTG gneisses are the oldest suites of the craton called the Sukma Group in view of its best development around Sukma in southern Bastar (Fig.3B-3). Sukma Group is also exposed prominently in the south and east of Bailadila Hills, near Gidam, Dantewara, Bijapur and Pakhanjur, and as scattered enclaves up to Dongargarh Granite.

Since each enclave has a limited number of (maximum of two or three) lithotypes in various combinations without any top-and-bottom criteria, it is difficult to build the traditional stratigraphy based on the order of superposition, and therefore it has to be model-dependent. The dominant lithological association is quartzite-carbonate-pelite-BIF, and therefore the favoured stratigraphy of Sukma Group is based on the continental interior or marginal basin models, and is given in Table 3B-2.

**Table 3B-2.** Stratigraphy of Sukma Group

| | |
|---|---|
| TTG gneisses (~ 3.0 Ga) | |
| Sukma Group | Banded iron formation (BIF) |
| | Amphibolites and ultramafics |
| | Cordierite-anthophyllite rocks |
| | Cordietite-andalusite-garnet-biotite schists, gneisses and quartzites |
| | Diopsidic calc-silicate rocks and para-amphibolites |
| | Sillimanite quartzite (±fuchsite, corundum, graphite) |
| Basement unknown (but may be 3.5 Ga gneisses) | |

Sillimanite quartzite forms prominent ridges near Sukma. The quartzite locally contains fuchsite, ruby-red corundum and graphite flakes. Sillimanite quartzite is associated with calc-silicate quartzite. The calc-silicate quartzite abounds in diopside, actinolite, epidote and sphene. Wollastonite and scapolite are reported from areas close to Bhopalpatnam granulite belt. Other calc-silicate rocks are closely associated with banded para-amphibolites rich in amphiboles and epidote. Cordierite-sillimanite gneisses are closely associated with quartzites and calc-silicate rocks. Locally, the cordierite gneisses are rich in garnet and some may contain andalusite. An interesting suite of cordierite-anthophyllite rocks abounds near Tirtam, Gidam and Ari Dongri. The suite contains cordierite, gedrite, anthophyllite, cummingtonite, garnet, and sometimes staurolite. In higher metamorphic grades, it contains orthopyroxene also. The cordierite-anthophyllite rocks are variously interpreted in literature as altered metavolcanic rocks or greywackes or hydrothermally altered mafic-ultramafic rocks. In Bastar craton, they contain gradational interbeds of quartzite and therefore are interpreted as wackes containing quartz, chlorite and some sericite. Banded iron formation is conspicuous in Sukma Group and is found scattered in several localities, particularly near Gidam. BIF appears to be mainly of silicate facies containing quartz, magnetite, grunerite, hornblende, garnet and locally orthopyroxene. BIF rich in hornblende and garnet with subordinate quartz may represent carbonate admixtures. Scattered lithologies of amphibolites (metavolcanics and dykes) and ultramafics (serpentinite, talc-tremolite schists, locally with pockets of chromite) are also found in the Sukma Group. Sukma rocks occur as clasts in the basal conglomerate of 'Purana' basins occurring in proximity to the scattered Sukma enclaves within gneisses.

*Structure and Metamorphism:* Structures in Sukma Group are complex, as the rocks are scattered within gneisses and granites as swathes and enclaves with variable orientation. The earliest phase is characterised by tight isoclinal folds, followed by the second phase open to tightly appressed folds and finally by open folds. Major folds are found in Kondagaon, Jagargonda, Bijapur, Toyanar and Pamed. Metamorphism is of low-pressure type, ranging from middle to upper amphibolite facies, and grades into granulite facies close to Bhopalpatnam and Kondagaon granulite belts.

*Age:* Sukma Group is not dated directly. Widespread Rb-Sr isochron ages of 2500-2600 Ma are recorded from gneisses in the areas where Sukma enclaves are abundant, but these may reflect regional metamorphic impress of Bengpal orogeny. Isolated Rb-Sr ages of gneisses are around 3000 Ma, with vestiges of 3500-3600 Ma determined by U-Pb and SHRIMP zircon ages from different areas. The age of Sukma Group is therefore reckoned at ~3000 Ma.

## Amgaon Group

Amgaon Group occurs in a ~100 km long and 20-30 km wide belt to the south of Sakoli belt around Gadchiroli, where Sukma-type lithologies occur within migmatites and grade into granulites in the NW extensions of Bhopalpatnam granulite belt. The line of demarcation between Sukma and Amgaon Groups in this region is uncertain. In the area to the east of Sakoli belt, the Amgaon enclaves consist of quartzites, calc-silicate rocks, marbles, garnet-staurolite-kyanite-sillimanite-mica schists, cordierite-anthophyllite rocks, amphibolites, chromiferous ultramafics and subordinate BIF. Most enclaves are similar to that of Sukma Group, but for the staurolite-kyanite-sillimanite-mica schists. The dividing line between Sukma and Amgaon Groups is uncertain in this area also. Similar enclaves are seen within the Amgaon gneisses occurring to the north of Sakoli belt. Amgaon gneisses of this area are in tectonic contact with Tirodi gneisses that surround the Sausar belt, along the Central Indian Shear Zone (CISZ). The correlation between the enclaves in Amgaon and Tirodi gneisses is ambiguous, since the enclaves in Tirodi gneisses are described variously as equivalents of either the Sausar or pre-Sausar sequence. Moreover, the terrane boundary shear zone of CISZ separates Tirodi and Amgaon gneisses, making the correlation very tenuous.

Amgaon Group of enclaves is marked by polyphase deformation and intermediate-pressure metamorphism. The enclosing gneiss yields dates of younger events (~2300 Ma) and therefore the age of Amgaon Group is uncertain.

## Gneissic Complex

Grey gneisses and migmatites of TTG composition are exposed in southern Bastar and in Amgaon-Gadchiroli areas. Banded gneisses occur as large rafts within the dominant granitic gneisses of the area, as at Aranpur, Mokhpal and Bijapur in southern Bastar and at Gadchiroli in Maharashtra. These migmatitic gneisses are dated at ~3000 Ma with relics of ~3600 Ma as at Markampara and Kapsi (Ghosh, 2004). These gneisses are affected by the later thermal events of ~2500 Ma and ~2100 Ma.

## Granulite Belts

*Bhopalpatnam granulite belt* (Bh in Figs.3B-1 and 3B-2) is about 300 km long and 30-40 km wide, and trends NW-SE to the north of Godavari graben, corresponding to the Karimnagar granulite belt of Dharwar craton in the south. The Sukma and Amgaon lithologies are upgraded into granulite facies when occurring in association with charnockites. Incipient charnockites are also reported to occur in the transitional domain. Meta-peridotites contain olivine, spinel and orthopyroxene. BIF and Mg-Al pelites are composed of orthopyroxene, sapphirine and spinel. Quartzites are rich in sillimanite. Calc-silicate rocks contain wollastonite, scapolite and humite (Prakash Narasimha et al. 1996). Recently reported younger age (1.6-1.9 Ga) of the belt (Santosh et al. 2004) may signify the impress of younger events on this belt.

*Kondagaon granulite belt* is a 70 km long, N-S trending belt occurring to the north of Indravati basin. Since this granulite belt occurs in the midst of the craton, it appears to be an uplifted horst-like structure within the basement. This inference is supported by the presence of sharp shear zones at its eastern and western margins. This belt appears as a gravity-high in the regional Bouguer anomaly map. Charnockites and leptynites dominate the western part of the granulite belt. Metapelitic enclaves are comparable to those of Sukma Group. To the east of the granulite belt, pillow lavas of Bengpal Group are preserved as enclaves in younger granites.

The Kondagaon granulite belt indicates ages of around 2600 Ma, similar to those of Karimnagar granulite belt.

## Bengpal Group

Bengpal Group occurs in a synclinorium plunging SSE that extends from near Bailadila to Tulsi Dongar Hills close to the Eastern Ghats mobile belt. Bengpal belt is bounded by a shear zone in the east that marks the western boundary of the transitional zone of the Eastern Ghats mobile belt. The eastern part of Bengpal belt is partly concealed by the Indravati basin to the north and Sabari basin to the south. The western part of Bengpal belt is marked by its deflection of strike from NW to N-S around Gidam coinciding with the Bailadila trend. The deflection of the trend is attributed to the impress of younger Bailadila deformation on the older Bengpal rocks. Structural basins of Chandenar in the west and Tulsi Dongar in the east expose good successions of Bengpal Group. Some workers assign younger stratigraphic positions to these basins. The folded angular unconformity between the Sukma enclaves and the coherent basalt-pelite-quartzite succession of Bengpal Group in Chandenar basin rules out the younger stratigraphic position of the basin (Fig.3B-4). Similar regional structural discordance is seen at Talem. Lithological association of basalt-pelite-quartzite in Tulsi Dongar is also comparable to the type area of Bengpal Group in Jhiram valley. The Chandenar and Tulsi Dongar basinal successions correspond respectively to Crookshank's Dantewara and Tulsi Dongar 'Stages' of Bengpal 'Series'. Crookshank (1963) emphasized however that his 'stages' are lateral facies equivalents and do not indicate the vertical order of superposition, and are so named only for descriptive convenience. The lithostratigraphy of Bengpal Group is tabulated below:

| | |
|---|---|
| Bengpal Group | Andalusite (and chiastolite) phyllites and schists (metamorphosed to sillimanite mica schists containing quartz-fibrolite nodules in Jhiram area), and andalusite-garnet quartzites |
| | Chloritoid-chlorite schists |
| | Amygdular metabasalts (locally pillowed) |
| | Quartz-sericite schists and sericite quartzites |
| | Older Gneissic Complex with swathes and enclaves of Sukma Group |

*Quartz-sericite schists*: Small bands of sericite quartzites associated with quartz-sericite schists are exposed at the base of the succession, overlain by metabasalts. This unit seen at places (e.g. Kaklur) *probably* marks the unconformity over the Older Gneissic Complex in southern Bastar.

*Metabasalts*: Dark grey fine to medium grained rocks (greenstones and greenschists) containing actinolite, sodic plagioclase, chlorite, epidote and opaques occur as large masses capping the high hills of Koleng, Mundval, Bengpal, Talem and Chandenar. Schistose rocks rich in chlorite are described in literature as basaltic tuffs, but these may as well be highly deformed meta-basalt. Large amygdales rich in quartz, calcite, actinolite and chlorite, circular to oval shape in plan, are a conspicuous feature of these metabasalts. In Jhiram area, these rocks are metamorphically upgraded to amphibolites, but still retain their amygdular structure. Rare pillows are recorded in the Kondagaon and Aridongri areas. Preliminary geochemical studies of Bengpal metabasalts indicate them to be high Fe tholeiites and rarely high Mg tholeiites and siliceous high magnesium basalts (SHMB) as well as boninites. This is probably the first report of boninite from the Precambrian of India (Srivastava, 2006). These lava types whose mutual field relations are unclear, show significant differences in their geochemistry and petrogenesis (Srivastava et al. 2004). Multi-elemental plots and REE patterns of these basaltic types are shown in Figs.3B-6a and b.

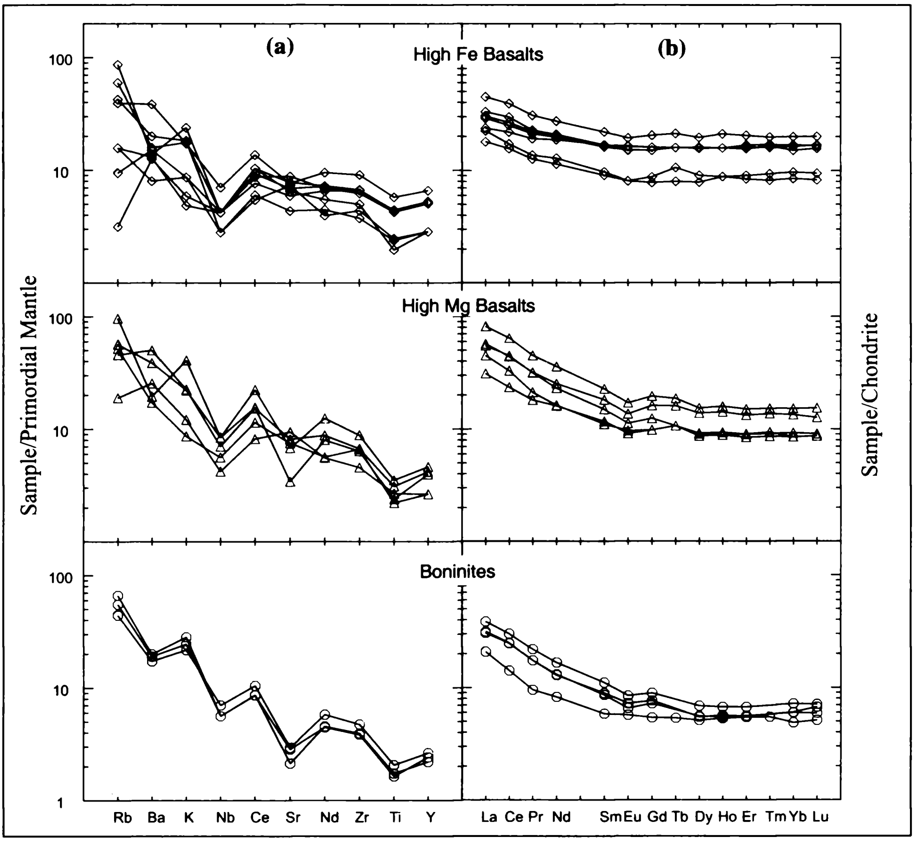


**Fig.3B-6.** (a) Primordial mantle-normalised multi-elements plots and (b) chondrite normalised rare-earth element patters for the southern Bastar mafic volcanic rocks (after Srivastava et al. 2004; Srivastava, 2005).

*Andalusite schists*: Ash grey to brownish schists and phyllites rich in chiastolite and grey andalusite occur as several interbeds within amygdular metabasalt. The diagonal cross of chiastolite sometimes contains chloritoid needles. Arenaceous schists rich in biotite, quartzites rich in garnet and andalusite, and tourmaline schists are of local importance. Chloritoid-chlorite schists are conspicuous in the Chandenar-Dantewara area. Fibrolite nodules of various shapes, sizes and concentration are abundant in the biotite-muscovite-garnet schists of Jhiram area. These resemble the sillimanite 'tabloids' (quartz-fibrolite nodules) described from Sausar belt. The mica schists are migmatised at the contact of Darba-Jhiram granites, and are marked by felspathisation and quartzofelpathic veining.

*Quartzites and conglomerates*: Interbeds of cross-bedded and ripple-marked quartzites and quartz-pebble conglomerate are seen within the metabasalt-andalusite schist association of Chandenar and Tulsi Dongar. These quartzites locally contain large andalusite crystals and are rich in biotite.

*Structure:* Bengpal Group is involved in complex isoclinal to reclined folding, probably of more than one phase, but details are lacking to obtain a regional picture. On the whole, Bengpal belt appears to form a regional synclinorium plunging towards southeast, as seen in the fanning of rocks from a narrow band in the northwest near Dantewara into a wide belt in the southeast near Tulsi Dongar.

Bengpal Group is dated with reference to granites that intrude the supracrustals. Most of the dates are Rb-Sr isochrons of ~2500-2600 Ma. Darba and Paliam granites yield dates of about ~2300 Ma that may reflect a younger metamorphic event. The age bracket of Bengpal Group is between 2500 and 2600 Ma.

## Kotri-Dongargarh Orogen

### Bailadala Group

Bailadila Hills, representing the type area for Bailadila Group, form the southernmost part of the Kotri-Dongargarh orogen (Figs.3B-2 and 3B-3). Bailadila Hills host rich iron ore deposits that are extensively mined. The iron ore deposits extend from the north of Bailadila to Rowghat and Dalli-Rajhara that contribute iron ores to the Bhilai Steel Plant. Bailadila Group is also preserved around the edges of the flat-lying Abujhmar basin, and forms folded keels near Surajgarh. Bailadila Group consists predominantly of Superior-type banded iron formation, in association with fine clastics and tuffs, and minor basic volcanics. The E-W and NNW-trending Sukma Group as well as WNW-trending Bengpal Group are swept into parallelism with the N-S trending Bailadila Group from west of Gidam to Bailadila Hills (Fig.3B-3) concurrent with the deformation of Bailadila Group. Sukma Group forms a garland around Bailadila Hills with an intervening gneissic country. Bengpal Group forms the foundation on which the Bailadila Group is laid and is deformed together during the major Bailadila deformation.

*Stratigraphic Problems:* Crookshank (1963) included the metabasalt-andalusite phyllite-Loa conglomerate succession, exposed at the foot of Bailadila Hills, in his Loa 'Stage' of Bengpal Group. Bandyopadhyay and Hishikar (1977) opined that Loa conglomerate occurs in the middle part of Bailadila Group. Khan and Bhattacharyya (1993) accepted the stratigraphic position of Loa conglomerate in the middle part of Bailadila Group, but felt that the metabasalt-andalusite phyllite association exposed in the foothills forms the basal part of Bailadila Group. Since the regionally extensive metabasalt-andalusite phyllite/schist association is characteristic of Bengpal Group, and since Bailadila and Bengpal Groups are separated by a quartzite marking an unconformity, the metabasalt-andalusite phyllite association is regarded here as part of Bengpal Group (Ramakrishnan, 1990). Bailadila Group has been classified into various formations by different authors, but for want of consensus, only the lithological associations are described here.

Lithostratigraphy of Bailadila Group is tabulated below:

| | |
|---|---|
| | Granites |
| Bailadila Group | Banded iron formation<br>Chloritic and sericitic phyllites with local interbeds of polymict conglomerate (Loa Conglomerate) and minor bands of mafic-ultramafic rocks<br>Felspathic quartzite |
| | - - - - - - - - - - - - - - - - -Unconformity - - - - - - - - |
| Bengpal Group | Metavolcanics and andalusite schists |
| | Unconformity |
| | - - - - Gneissic Complex with enclaves of Sukma Group - - - - |

The basal feldspathic to arkosic quartzites are cross-bedded, with thin intercalations of phyllites and meta-siltstones. The quartzite is locally underlain by phyllitic conglomerate containing pebbles of Bengpal Group. The quartzites consist essentially of quartz, kaolinised felspars and white mica.

The chloritic and sericitic phyllites occupy the middle flanks of Bailadila Hills. The phyllites are usually grey to olive green in colour with sericite, chlorite and quartz as important constituents. Locally they contain large muscovite flakes. The phyllites are at places carbonaceous and resemble 'black shales' usually associated with iron formations. Grey cherts and cherty shales occur as thin bands in phyllites close to the iron formation. The grey phyllites are associated with the prominent polymict conglomerate (Loa conglomerate), which was earlier, correlated with Bengpal Group, but now has been shown to occur as interbeds within the phyllites of Bailadila Group. The conglomerate carries clasts of quartzites, metabasalts and iron formations derived from the uplift and erosion of Bengpal and Sukma Groups as well as the gneissic basement. The situation is similar to that of iron formation basins of Bababudan Group in Dharwar craton. Minor sills of basic and ultrabasic rocks are found within the thick phyllitic sequence.

The iron formations of Bailadila Group are rich in hematite and martite, with rare chlorite and grunerite. Magnesio-riebeckite and aegirine are confined to some bands, as in the Bababudan Group of Dharwar craton, Transvaal Group of South Africa and Hamersley Group of Australia. This mineralogical association appears to be compositionally controlled and occurs in bands rich in alkali and magnesium within the BIF.

Two main phases of deformation are recorded in Bailadila Group, the earlier intensive phase with tight folds having N-S to NNE-SSW axes plunging steeply towards the south and northeast, and the later phase with NW-SE trending folds plunging moderately northwest. The major structure of the Bailadila basin is interpreted as two main synclines separated by intervening anticline.

The age of Bailadila Group is not well-constrained. It is tentatively bracketed between the ages of the underlying Bengpal Group and the overlying Nangaon Group at ~2400 Ma.

### Nandgaon Group

Bailadila Group is unconformably overlain by a sequence of bimodal felsic to mafic volcanics belonging to Nandagaon Group that is well exposed between Dongargarh Granite and Chhattisgarh basin. In the area to the north of Bailadila Hills beyond the Indravati River up to Dongargarh Granite, the equivalent rocks in strike extension are called by the name Ainhur Group, whose basal beds are called the Dargah Formation, and the overlying felsic and mafic volcanics by other local names. Lithostratigraphic succession of this Nandgaon Group is given below:

Pitepani Basalt
Bijli Ryolite
Dargah Formation

Yedekar et al. (2003) describe Pitepani Basalt as underlying Bijli Rhyolite, contrary to the consensus of earlier workers. These authors also report the occurrence metabasalt near Amgaon as underlying Nandgaon Group.

A thin sedimentary unit called Dargah Formation overlies Bailadila Group and consists of conglomerates, arkosic sandstone and argillites exposed near Dargah and along the Kotri River section. The conglomerate consists of pebbles of granite gneiss, quartzite and vein quartz, cemented by quartzo-felspathic matrix, and is intruded by quartz porphyry. Bijli Rhyolite consists predominantly of rhyolite and high-silica rhyolite with minor rhyodacite and dacite as well as felsic agglomerates and tuffs. The rhyolite is a dark grey glassy rock showing vesicular and spherulitic structures and flow banding. The agglomerate consists of clasts of rhyolite, granophyre, quartzite, amphibolite, gneiss, chert and jasper set in a fused rhyolitic matrix. Granophyre is developed at the contact of Dongargarh Granite and the rhyolite. Rhyolitic tuff consists of lithic fragments of rhyolite, chert, BIF and quartzite. These rhyolites are potassic peraluminous types, which are comparable with Dongargarh Granite. They are enriched in LREE, Zr, Th, Cr and depleted in LILE, Ti, Sc, Y and Ni. Bijli rhyolites are interpreted as a product of interaction of high-Mg basalt with granulites and gneisses (Sensarma et al. 2004). Pitepani Basalt was earlier described as andesite on the basis of colour index, but recent geochemical studies have shown it dominantly to be basalt and basaltic andesite, showing tholeiite trends. Locally there are occurrences of basaltic and pyroxenitic komatiites, with spinifex texture. Some flows are layered and some others are amygdular. Lithic tuffs consisting of fragments of vein quartz, chert and jasper are also found. This volcanic association (Bijli, Pitepani) is comparable to the ubiquitous bimodal mafic-felsic volcanics found in Precambrian belts. The early lavas are LREE enriched and highly fractionated rhyolites to progressively less fractionated patterns in mafic volcanics, consistent with derivation of felsic and mafic lavas by progressively higher degree of melting of a common source. A possible crustal contamination is indicated for the voluminous rhyolites by high LILE and LREE ratios.

Nandgaon Group is not extensively deformed, but N-S trending folds and faults are fairly common. The rhyolites of Nandgaon Group yield Rb-Sr whole rock isochron ages of ~2300 Ma.

### Khairagarh Group

The sandstone-basalt alternations of Khairagarh Group overlie the Nandgaon Group and Dongargarh Granite. This group occurs in a doubly plunging syncline with axes trending NNE-SSW, to the north of Dongargarh. It is separated from the Nandgaon Group by an eruptive unconformity marked by Dongargarh Granite. Previous workers have clubbed Nandgaon and Khairagarh Groups, together with Dongargarh Granite, into Dongargarh Supergroup. In view of the intervening major granitic episode, all the three units are retained here as independent groups.

The stratigraphy of Khairagarh Group is given below:

| | |
|---|---|
| Khairagarh Group | Ghogra Sandstone |
| | Mangikhuta Basalt |
| | Karutola Sandstone |
| | Sitagota Basalt |
| | Bortalao Sandstone |

Bortalao Sandstone is the major basal formation consisting of conglomerates, arkosic arenite, siltstone and shale. Felsic tuff is recorded in this formation at some places. The shale is locally ferruginous. Sitagota Basalt comprises massive, porphyritic and amygdular basalts containing xenoliths of Bortalao Sandstone. The basalt is associated with agglomerate and tuff, and exhibits quench texture (Fig.3B-7a) and variolitic structure (Fig.3B-7b). Sitagota

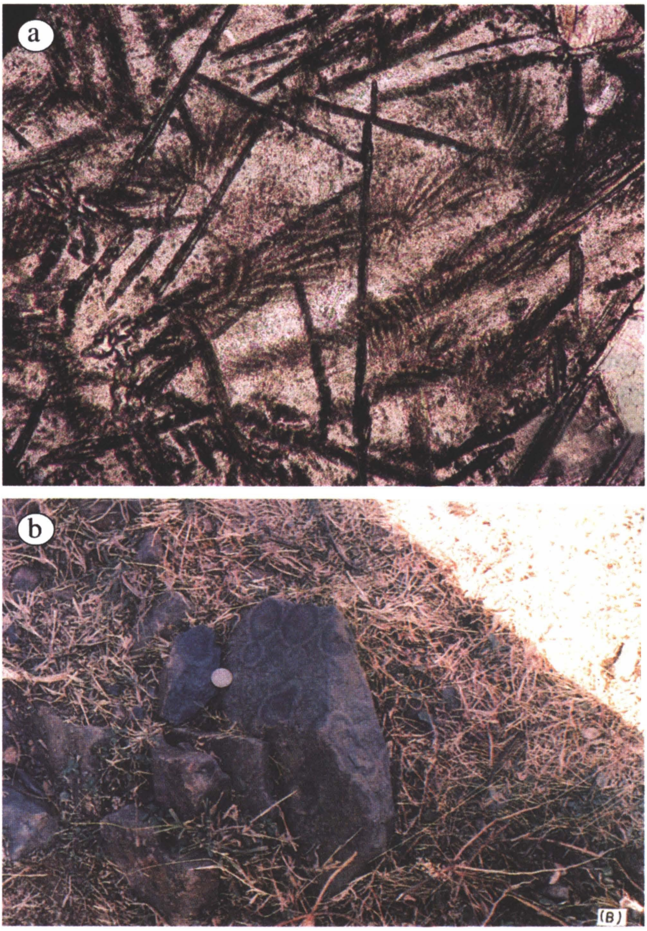


**Fig.3B-7.** (**a**) Quench structure in Sitagota volcanics. (Nicols crossed X 75; *JGSI*, v.70, p.790, 2007). (**b**) Varioles in Sitagota volcanics near Murdoli (from Deshpande et al. 1990).

volcanics are essentially tholeiitic basalts to basaltic andesites with rare picrites. Basaltic and pyroxenitic komatiites and siliceous high magnesian basalts (SHMB) of boninitic affinity are also reported. This is probably the first report of SHMB in the Precambrian of India (Sensarma et al. 2002). The excess of incompatible elements and high $SiO_2$ in SHMB is possibly the result of the basaltic komatiite parent magma of mantle origin assimilating the felsic volcanics of Nandgaon Group. The volcanics are unfractionated and primitive as seen in their flat REE patterns, high Mg# and high compatible element contents.

Although the lavas of Dongargarh belt have close chemical affinity with island arc magmas, the associated sediments point to a stable continental margin setting. A continental rift environment is therefore suggested for the Dongargarh (Nandgaon and Khairagarh Groups) volcanics. The age of Khairagarh Group is uncertain since only the mineral ages of ~1800 Ma signifying younger events are recorded so far.

### Chilpi Group

The predominantly low-grade metasediments of Chilpi Group are well exposed in the type area of Chilpi Ghat section on the Chilpi-Bilaspur road. The Chilpi rocks skirt round the northwestern margin of the Chhattisgarh basin and extend further as Bilaspur-Raigarh belt. They also unconformably overlie the Malanjkhand Granite and Nandgaon Group in the west. The general N-S structural trend of Chilpi Group is in conformity with the other groups of Kotri-Dongargarh orogen, but the trend swerves to E-W adjacent to the Central Indian Shear Zone (CISZ).

Chilpi Group commences with conglomerate and coarse arenite (grit) containing clasts of volcanic rocks. The main rock units of the group are chloritic and sericitic phyllites and banded cherts. Crystalline limestones are associated with cherts and manganiferous bands. At places, small outcrops of rhyolitic ignimbrites are described from this group.

Although the age of the Chilpi Group is not known with certainty, it may be >1800 Ma old, by comparison with Sakoli and Khairagarh Groups.

### Abujhmar Group

The intracratonic basin covering 3000 $km^2$ called the Abujhmar (meaning Unknown Hills) overlies the Bailadila and Nandgaon Groups within the Kotri-Dongargarh orogen. This basin is described in Chapter 5.

### Sakoli and Sonakhan Belts

Parallel to the N-S trending Kotri-Dongargarh orogen are isolated supracrustal belts of Sakoli to the west and Sonakhan to the east, situated within gneisses and granites. Their lithologies are correlatable with parts of Kotri-Dongargarh orogen.

### Sakoli Group

Sakoli belt (Fig.3B-8), covering an area of 3500 km$^2$, is a triangular belt, which occurs at the convergence of three major tectonic trend lines viz. the Satpura mobile belt, Kotri-Dongargarh orogen, and the third trend parallel to Godavari graben shouldered by Bhopalpatnam granulite belt. The triangular outcrop pattern of Sakoli and Sausar belts was described in earlier literature (Bhattacharjee, 1937) as Bhandara triangle that led Naqvi and Rogers (1987) to call this region as Bhandara craton. The rock assemblage of the belt is dominated by metapelites (~80%) with subordinate felsic to mafic bimodal volcanics (~20%). Amgaon Gneiss forms the basement, but the basement-cover relationship is obliterated due to later shearing. The generalised litho-stratigraphic of Sakoli Group is given below (after A. Roy *in* Bandyopadhyay et al. 1995):

| | |
|---|---|
| Pawni Formation | Slate, phyllite, arkose, quartz-arenite and conglomerate |
| Bhiwapur Formation | Mainly metapelites (± chloritoid, andalusite, garnet, staurolite) with interbands of felsic volcanics/tuffs and exhalative sediments (coticules, tourmalinites, chloritites, BIF), rare basalts; and Zn-Cu, Au and scheelite mineralisation |
| Dhabetekri Formation | Mainly metabasalts, with minor ultramafics, cherts, metapelites and BIF |
| Gaikhuri Formation | Conglomerate, coarse arenite, arkose, minor pelites (partly carbonaceous) and BIF |
| | ---------------Unconformity----------------- |
| | Amgaon Gneiss and Supracrustals |

Later suggestions for modifying the stratigraphy (Chawade and Naik, 2003) involved the renaming of the basal formation, clubbing different lithological units between Dhabetekri and Bhiwapur Formations, viewing Pawni Formation as post-Sakoli, and emphasizing the stratigraphic importance of the newly identified Pawni-Gangajhari fault. There are also unresolved debates on the surrounding gneisses being intrusive or basement.

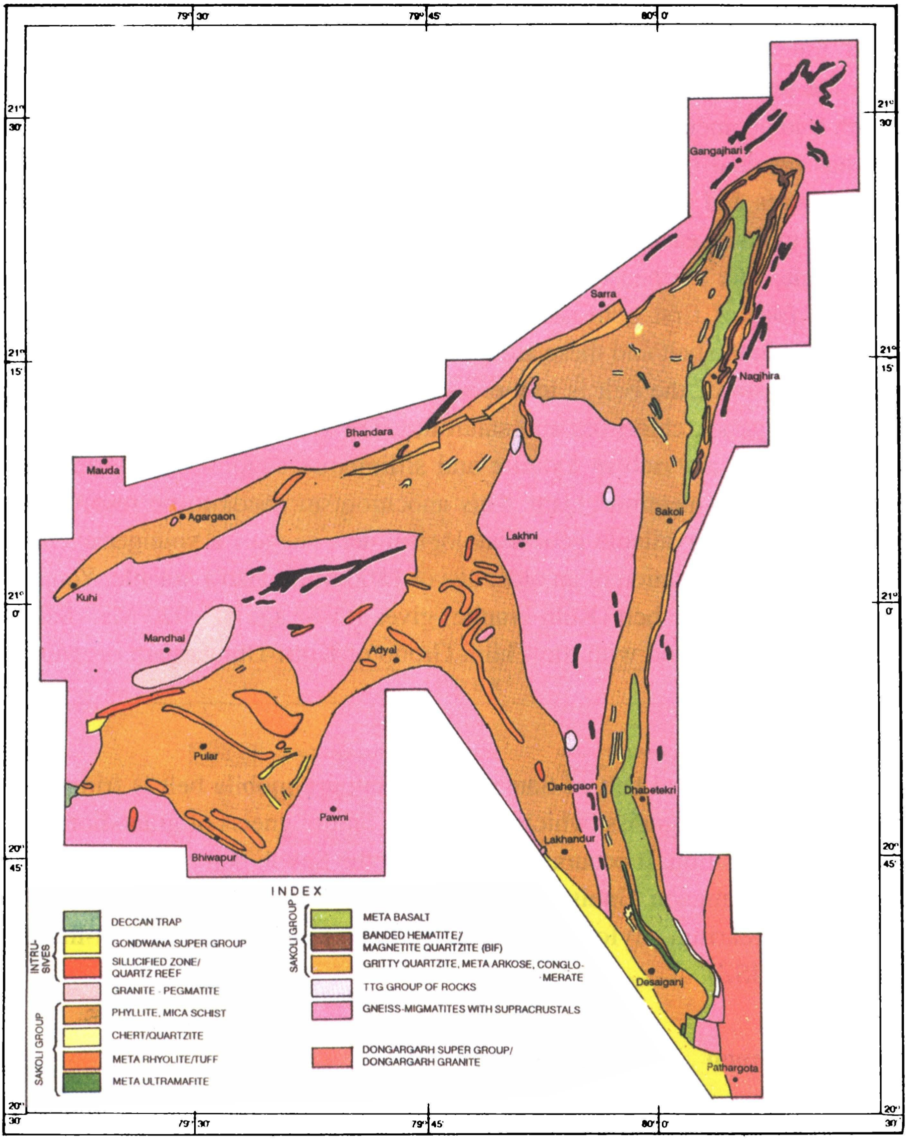

79°30'
79°45'
80°0'
21°30'
21°15'
21°0'
20°45'
20°30'
Gangajhari
Sarra
Nagjhira
Bhandara
Mauda
Agargaon
Sakoli
Lakhni
Kuhi
Mandhal
Adyal
Pular
Pawni
Bhiwapur
Dahegaon
Dhabetekri
Lakhandur
Desaiganj
Pathargota
INDEX
DECCAN TRAP
INTRUSIVES
GONDWANA SUPER GROUP
SILLICIFIED ZONE/ QUARTZ REEF
GRANITE - PEGMATITE
SAKOLI GROUP
PHYLLITE, MICA SCHIST
CHERT/QUARTZITE
META RHYOLITE/TUFF
META ULTRAMAFITE
SAKOLI GROUP
META BASALT
BANDED HEMATITE/ MAGNETITE QUARTZITE (BIF)
GRITTY QUARTZITE, META ARKOSE, CONGLOMERATE
TTG GROUP OF ROCKS
GNEISS-MIGMATITES WITH SUPRACRUSTALS
DONGARGARH SUPER GROUP/ DONGARGARH GRANITE

**Fig.3B-8.** Geological map of Sakoli belt (after Bandyopadhyay et al. 1995).

Sakoli mafic volcanics are mainly evolved tholeiites. The mafic and felsic volcanics are believed to have originated from different sources, with the felsic volcanics having been derived from the partial melting of sialic crust. An important feature of the Sakoli succession is the presence of a variety of mineralised exhalites like coticules and tourmalinites. Coticules are cherts rich in manganese garnet (spessartite), and tourmalinites are layered tourmaline-quartz rocks. BIF is fairly common as small isolated bands. Garnet-amphibole rocks represent silicate facies iron formation enriched in Ca. These rocks play host to Sedex-type stratiform and stratabound sulphide (Cu-Zn) and scheelite (gold, tungsten) mineralisation.

The regional structure of the belt is a doubly plunging synclinorium with sheath fold geometry on NE-SW axial plane. The triangular map pattern of the belt has resulted from a combination of initial basin geometry modified by fold closures and ductile shear zones. There are two prominent shear zones viz., N-S trending eastern margin shear zone and ENE trending northern margin shear zone. The northeast tip of Sakoli triangle near Gondia is a vertical or reclined fold of first generation. There are four episodes of deformation recognised in the belt and these are related to meso- to macroscopic structures. Metamorphism of the belt is low-pressure type, as reflected by the minerals andalusite, garnet, chloritoid and staurolite. The enclaves in the gneisses, on the other hand are rich in kyanite and sillimanite suggesting intermediate pressure type of metamorphism. This anochronism needs to be resolved by future work. The available geochronological data suggest a younger event of ~1300 Ma, but indication of an older age of 1800 Ma is also available. Younger granite intruding the belt (Kuhi granite) gives Rb-Sr age of ~920 Ma. Sakoli belt may be correlated with the Chilpi Group of Kotri-Dongargarh orogen.

### Tirodi Gneiss

The supracrustal belt of Sausar in the Satpura mobile belt is fringed on the south by Tirodi gneiss, which is largely a biotite gneiss of granodioritic to granitic composition. It occurs to the north of the Sakoli belt and is in tectonic contact with Amgaon Gneiss of Bastar craton. Tirodi gneiss is involved in extensive shearing, mylonitisation and 'reworking' at the craton-mobile boundary (CISZ).

### Sonakhan Group

The isolated, NW-trending Sonakhan belt (Fig.3B-9), covering an area of 1000 sq. km, underlies the Chhattisgarh basin, and is in tectonic and intrusive contact with the surrounding gneiss, locally called as Baya gneiss, that consists of composite gneisses and foliated to even grained granites. Baya gneiss is seen as NNW trending domes. Since Sonakhan belt is predominantly a volcanic belt, it has been termed as schist belt or greenstone belt, in comparison with those of the Dharwar craton. The lithostratigraphy of the belt is given below (Das et al. 1990; Saha et al. 2000).

| | |
|---|---|
| | Arjuni Formation |
| Sonakhan Group | Unconformity |
| | Baghmara Formation/ Bilari Formation |

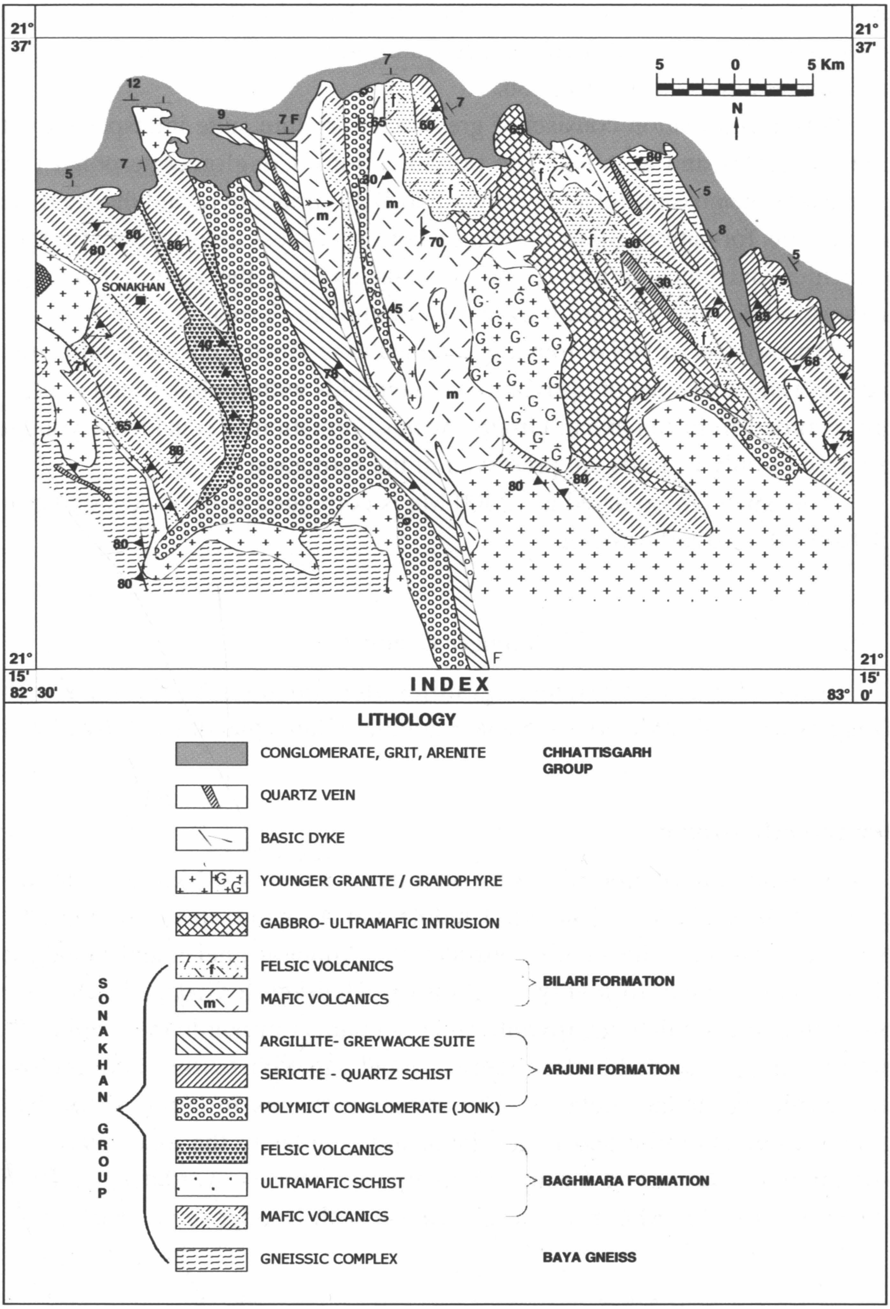

21° 37'
21° 15'
82° 30'
83° 0'
5 0 5 Km
N
SONAKHAN
F
INDEX
LITHOLOGY
CONGLOMERATE, GRIT, ARENITE
CHHATTISGARH GROUP
QUARTZ VEIN
BASIC DYKE
YOUNGER GRANITE / GRANOPHYRE
GABBRO- ULTRAMAFIC INTRUSION
FELSIC VOLCANICS
MAFIC VOLCANICS
BILARI FORMATION
ARGILLITE- GREYWACKE SUITE
SERICITE - QUARTZ SCHIST
POLYMICT CONGLOMERATE (JONK)
ARJUNI FORMATION
FELSIC VOLCANICS
ULTRAMAFIC SCHIST
MAFIC VOLCANICS
BAGHMARA FORMATION
GNEISSIC COMPLEX
BAYA GNEISS
SONAKHAN GROUP

**Fig.3B-9.** Geological map of Sonakhan belt (after Das et al. 1990).

Baghmara Formation consists essentially of metabasalts, basaltic hyaloclastites, felsic volcanics and BIF. The metabasalts are locally pillowed and amygdular. They are massive and schistose depending on the degree of deformation. Rhyolites and rhyodacites are associated with pyroclastic air fall and flow deposits and some are ignimbrites/welded tuffs. Greywacke, black shale and BIF show local development. Gabbro-ultramafic rock, felsic porphyry and diorite intrude this formation.

Arjuni Formation consists of greywacke-argillite suite interspersed with conglomerates and arenites. The polymict Jonk Conglomerate consists of pebbles of metabasalt, felsic porphyry and BIF. Granophyre and diorite dykes intrude this formation. Bilari Formation consists of less deformed mafic-felsic volcanics and volcaniclastics, and is considered as the youngest by some authors, while others regard it as part of Baghmara Formation.

An early set of NNW trending inclined to reclined folds with subvertical axis ($F_1$) and a later set of upright to inclined folds with subhorizontal axis ($F_2$) are recorded from Sonakhan Group. Arjuni Formation is considered younger because of only $F_2$ folds are preserved in the formation.

Sonakhan Group dated at ~2300 Ma is correlated with Nandgaon Group of Kotri-Dongargarh orogen.

## Younger Granites

Major bodies of younger granites that intrude the craton are the Dongargarh, Malanjkhand and Kanker granites (Ramachandra and Roy, 1998).

### Dongargarh Granite

Dongargarh Granite, covering an area of about 8000 km$^2$, occurs as a group of three plutons (Dhanora, Chidole and Amgaon) in the southwest of Nandgaon Group. The granite intrudes the Amgaon gneiss and Nandgaon Group and is unconformably overlain by Khairagarh Group. Enclaves of migmatite, metasediments, rhyolite and basalt are common in the granite. The granite shows magmatic flow fabrics, local rapakivi texture and encloses mafic microgranular enclaves. The intrusion ranges in composition from granite to granodiorite and is geochemically similar to the associated felsic volcanics of Nandgaon Group. Dongargarh granites are dated by Rb-Sr isochrons at ~2300 Ma, that is nearly coeval with Nandgaon volcanics.

### Malanjkhand Granite

It is an elongate N-S trending pluton of about 1000 km$^2$ area and ranges in composition from granite to granodiorite, with some areas of tonalite. Like the Dongargarh Granite, this granite also shows good magmatic fabrics. Small-scale shear zones traversing the granite are associated with copper mineralisation. The Malanjkhand copper deposit is one of the largest deposits in India, which is compared either to porphyry type or to hydrothermal type. This granite yields Rb-Sr isochron at ~2300 Ma.

### Kanker Granitoids

These are also very similar to the Dongargarh and Malanjkhand granites, covering an area of over 1000 km$^2$ and are mainly granitic in composition. They intrude the Sonakhan belt and are unconformably overlain by the Chhattisgarh basin.

## MAFIC DYKES

Mafic dykes and dyke swarms mark extensional regimes attendant on cratonisation. There are three major events of dyke formation (Ramachandra et al. 1995; Srivastava and Singh, 2004) recognised in Bastar craton (Fig.3B-10). The oldest dykes, which have a NNW trend parallel to the Godavari

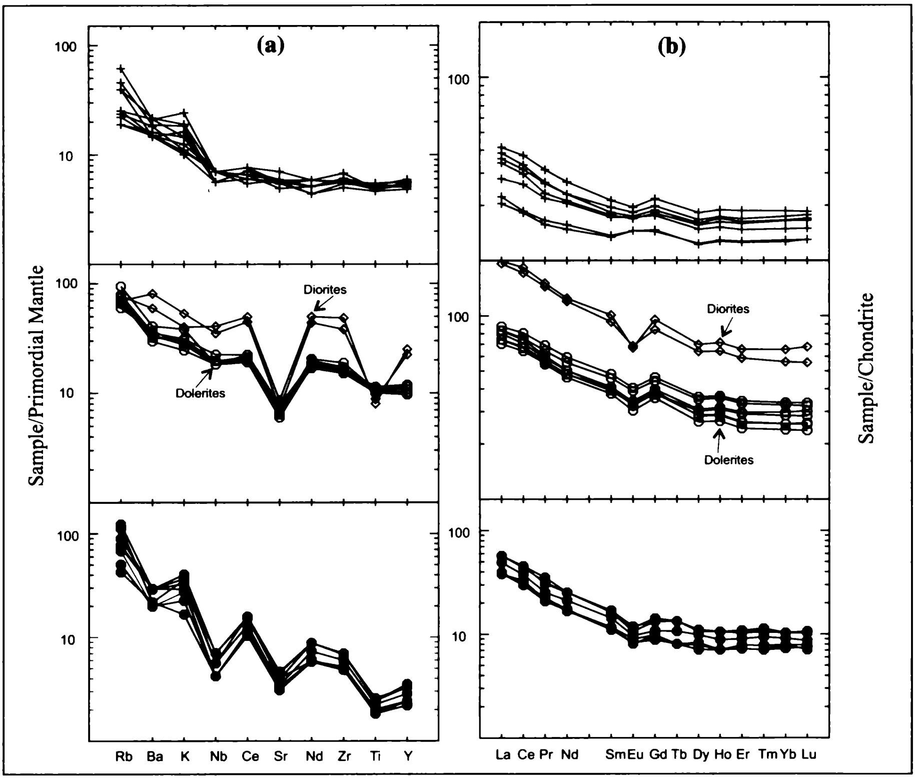


**Fig.3B-10.** (**a**) Primordial mantle-normalised multi-element plots and (**b**) Chondrite normalised rare-earth element patterns for the southern Bastar mafic dykes (Srivastava and Singh, 2004; Srivastava, 2005).

graben, are essentially amphibolites, consisting mainly of hornblende and plagioclase ($An_{20-60}$). These have generally low Ti (~1.7%), low Fe and moderate Mg (~6%) and are tholeiitic. At the intersection of two amphibolite dykes in some rare instances, the cross-cutting dyke preserves the igneous mineralogy and texture of dolerite. The amphibolite dykes intrude the Older Gneissic Complex but are intruded by younger granites and may be Neoarchaean in age. A unique set of actinolite-plagioclase dykes (epidiorite or greenstone) having coarse gabbroic texture traverse the gneissic complex as well as Bengpal Group sinuously and in a zigzag manner. These dykes have similar mineralogy and metamorphic grade (greenschist facies) to the Bengpal metabasalts, but for their coarse gabbroic texture, and may be feeder dykes to the basic lavas. They may correspond to the age of the Bengpal Group (~2500 Ma) that signifies the Archaean-Proterozoic transition. Recent geochemical studies have shown them to be high magnesian siliceous type or SHMB ($SiO_2$: 5.2%, MgO: ~12% and Ti: ~0.5%), similar to boninites. Incidentally, some of the Bengpal lavas as at Kaklur are also siliceous high magnesian basalts (SHMB). The next set of dykes is high-Fe tholeiites having high Ti (2.3%), high Fe (16-17% FeO) and low Mg (~4.5%). These are fresh to least altered dolerites. They yield bedelleyite TIMS U-Pb and U-Th-Pb chemical dates that show the Palaeoproterozoic emplacement age of 1900 Ma (French et al. 2004).

## TECTONIC EVOLUTION

The grey gneiss complex of Bastar craton preserves vestiges of early crustal history at 3500-3600 Ma. A widely scattered suite of enclaves of quartzite-pelite-carbonate suite (Sukma and Amgaon Groups) swamped by TTG gneisses is seen next at ~3000 Ma. On such a stabilised crust, a WNW-ESE rift was formed and was filled with amygdular basalt in association with clastics (andalusite phyllite and mica schists, quartzites) forming the Bengpal Group. This typical Proterozoic-type succession was formed in the craton at the Archaean-Proterozoic transition. Bengpal Group witnessed widespread intrusive granitic activity around ~2500-2600 Ma. The Bengpal event was followed by the initiation of a long-lived, narrow N-S trending continental rift called the Kotri-Dongargarh orogen. Initially, a Superior-type basin of banded iron formation (BIF) was formed that hosted rich iron ores of Bailadila, Rowghat and Dalli-Rajhara. These iron ores are mined for feeding the Bhilai and Visakhapatnam Steel Plants and for export purposes. The basinal succession is called Bailadila Group (~2400 Ma) after the Bailadila Hills (ox hump-shaped hills) and was made of basal quartzite, a dominant fine clastic and tuffaceous unit (phyllite with rare polymict Loa conglomerate) in the middle and extensive BIF on top. After a break in sedimentation, the new cycle of felsic and mafic volcanics (Nandgaon Group) ensued, with a basal conglomerate and quartzite. A major granitic pluton (Dongargarh Granite) that was coeval and probably comagmatic with the felsic volcanics intruded Nandgaon Group at about ~2300 Ma. Another volcanic-clastic cycle followed soon, consisting of alternations of basalts and sandstones (Khairagarh Group). The Khairagarh volcanic event concluded the main felsic to mafic volcanism in the continental rift of Dongargarh. A still younger succession of dominant fine clastic sediments associated with some chemical precipitates (Chilpi Group) formed the youngest unit of Kotri-Dongargarh orogen, probably after the cessation of the volcanic cycles in the Donargargarh rift, as evidenced by its spill over in the east on to the gneissic basement that includes the mineralised Malanjkhand Granite. Chilpi Group was involved in the intense E-W deformation of Satpura mobile belt (CITZ) at the northern boundary of the craton. The NNW-trending Sonakhan 'greenstone belt' formed in an isolated rift in the east within the gneissic complex, probably during the main volcanic phase (Nandgaon Group) of Dongargarh rift. The well-known triangular Sakoli belt occurring to the west of Kotri-Dongargarh orogen is probably contemporaneous with Chilpi Group and is involved in the deformation of Satpura mobile belt. The ages of Sakoli and Chilpi belts are not well constrained, but they are possibly involved in the younger ~1500-1600 Ma event of Satpura mobile belt. Bastar craton was fully stabilised by about 1800 Ma, which paved the way for the deposition of 'Purana' basins of Abujhmar, Chhattisgarh and Bastar.

# SINGHBHUM CRATON

## INTRODUCTION

Singhbhum craton (Fig.3S-1) covers a triangular area of 50,000 km$^2$ and consists of a core (8000 km$^2$) of Singhbhum granite, rimmed by supracrustals of varied character and age. The arcuate North Singhbhum orogen wraps round Singhbhum granite in the north. The well-known Singhbhum or Copper Belt shear zone occurs in the northern margin of Singhbhum granite, close to the southern margin of the North Singhbhum orogen. Singhbhum craton is bounded further in the north by the Chhotanagpur Gneiss, forming the eastern extension of the Satpura mobile belt or Central Indian Tectonic Zone (CITZ). The craton is separated from the Satpura mobile belt by the Tamar-Poropahar (or South Purulia) shear zone. In the south, the craton is bounded by the Eastern Ghats mobile belt with a tectonic contact marked by the Sukinda shear zone. In the east, the craton is covered under the alluvium of Bengal basin. Singhbhum craton is also called in literature as Singhbhum-Orissa craton or Singhbhum Iron Ore craton, but the name Singhbhum craton is widely used.

### Main Components

The craton consists of six principal lithological associations (Fig.3S-2) namely,

1. Singhbhum granite with enclaves of Older Metamorphic Tonalite Gneiss (OMTG) and Older Metamorphic Group (OMG) of sediments and volcanics.
2. Basins of banded iron formation (BIF) fringing the Singhbhum granite.
3. Volcanic basins, loosely termed as greenstone belts.
4. Flysch-like sediments and volcanics of North Singhbhum orogen.
5. Mafic dyke swarms.
6. Kolhan basin.

These lithological associations are briefly outlined below:

(1) The oval-shaped Singhbhum granite is a composite of several bodies, which are assigned to three phases (Phases I, II and III). The Phases I and II are geochemically distinguished as Type A of Singhbhum granite called SG-A (~3300-3400 Ma), and Phase III as Type B (SG-B, ~3100 Ma). Broadly,

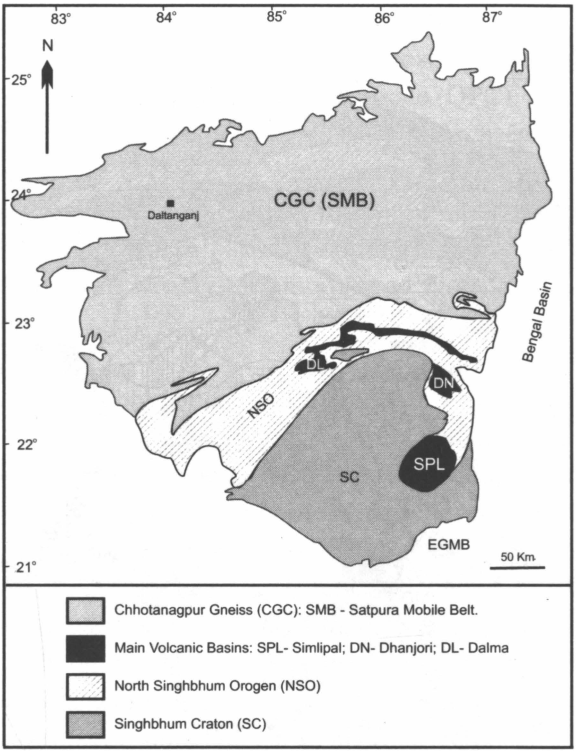

83°
84°
85°
86°
87°
N
25°
24°
23°
22°
21°
CGC (SMB)
Daltanganj
Bengal Basin
DL
DN
NSO
SPL
SC
EGMB
50 Km
Chhotanagpur Gneiss (CGC): SMB - Satpura Mobile Belt.
Main Volcanic Basins: SPL- Simlipal; DN- Dhanjori; DL- Dalma
North Singhbhum Orogen (NSO)
Singhbhum Craton (SC)

**Fig.3S-1.** Synoptic map of Singhbhum craton with adjacent orogen, volcanics and mobile belt (CGC) (after Misra, 2006). EGMB - Eastern Ghats Mobile Belt.

Singhbhum granite belongs to granodiorite-adamellite-granite (GAG) suite, containing 3300-3400 Ma old enclaves of OMG and OMTG. Kaptipada (Nilgiri) granite in the east, Chakradharpur granite in the north and Bonai granite in the west are correlatives of Singhbhum granite. The unclassified gneisses around Pala Lahara are called Pala Lahara gneiss that may also be correlated with Singhbhum granite.

(2) There are three basins of iron formation fringing the Singhbhum granite to the west, east and south, called respectively as Noamundi-Koira, Gorumahisani-Badampahar and Tonka-Daitari. They have been grouped by different authors either into a single Iron Ore Group or into two major stratigraphic groups of the older Badampahar Group and younger Koira Group. The Daitari Group is correlated by many authors with Badampahar Group.

(3) Isolated volcanic basins of varied ages occur in the craton and the marginal orogen. The volcanic basins overlying Singhbhum granite are the Simlipal and Dhanjori in the east, and Jagannathapur (Dungoaposi) and Malangtoli (Nuakot) in the west. Dalma volcanics occur within the North

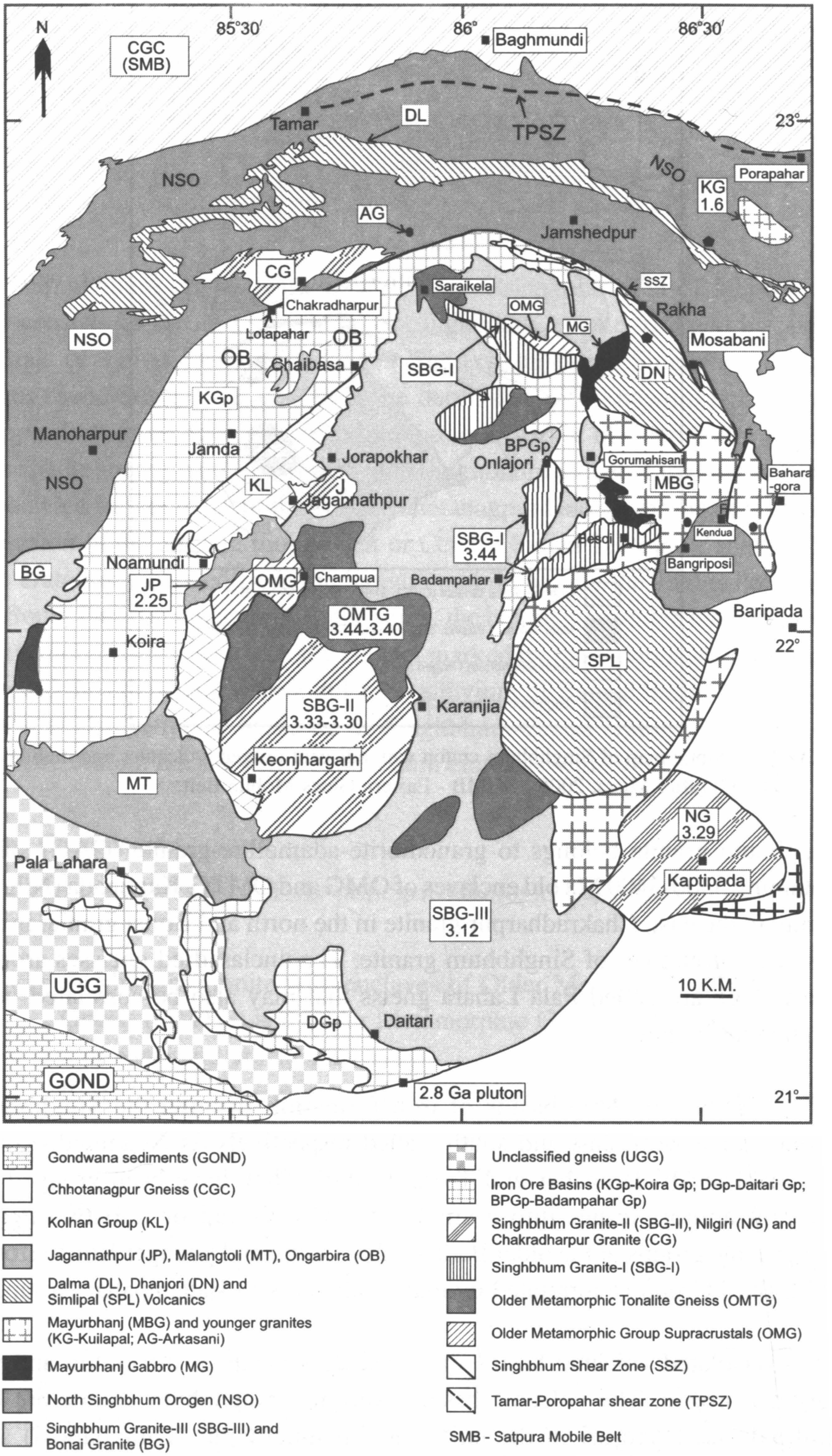

N
CGC (SMB)
85°30′
86°
Baghmundi
86°30′
Tamar
DL
TPSZ
23°
NSO
NSO
Porapahar
KG 1.6
AG
Jamshedpur
CG
Saraikela
SSZ
Chakradharpur
OMG
Rakha
NSO
Lotapahar
OB
MG
Mosabani
OB
Chaibasa
SBG-I
DN
KGp
Manoharpur
Jamda
BPGp
Jorapokhar
Onlajori
Gorumahisani
NSO
KL
J
MBG
Bahara-gora
Jagannathpur
F
SBG-I 3.44
Besoi
Kendua
Noamundi
Bangriposi
BG
JP 2.25
OMG
Champua
Badampahar
OMTG 3.44-3.40
Baripada
22°
Koira
SPL
SBG-II 3.33-3.30
Karanjia
Keonjhargarh
MT
NG 3.29
Pala Lahara
Kaptipada
SBG-III 3.12
UGG
10 K.M.
DGp
Daitari
GOND
2.8 Ga pluton
21°
Gondwana sediments (GOND)
Chhotanagpur Gneiss (CGC)
Kolhan Group (KL)
Jagannathpur (JP), Malangtoli (MT), Ongarbira (OB)
Dalma (DL), Dhanjori (DN) and Simlipal (SPL) Volcanics
Mayurbhanj (MBG) and younger granites (KG-Kuilapal; AG-Arkasani)
Mayurbhanj Gabbro (MG)
North Singhbhum Orogen (NSO)
Singhbhum Granite-III (SBG-III) and Bonai Granite (BG)
Unclassified gneiss (UGG)
Iron Ore Basins (KGp-Koira Gp; DGp-Daitari Gp; BPGp-Badampahar Gp)
Singhbhum Granite-II (SBG-II), Nilgiri (NG) and Chakradharpur Granite (CG)
Singhbhum Granite-I (SBG-I)
Older Metamorphic Tonalite Gneiss (OMTG)
Older Metamorphic Group Supracrustals (OMG)
Singhbhum Shear Zone (SSZ)
Tamar-Poropahar shear zone (TPSZ)
SMB - Satpura Mobile Belt

**Fig.3S-2.** Simplified geological map of Singhbhum and adjoining areas (after Misra, 2006).

Singhbhum orogen; Ongarbira volcanics overlie the Koira Group in the northwest. Dhanjori and Simlipal basins expose typical quartzite-basalt association with a basal quartz pebble conglomerate (QPC). Such a lithological ensemble denoting a stable crust occurs globally in Archaean cratons after the cessation of greenstone cycles e.g., Witwatersrand-Triad of southern Africa, Circum-Superior basins of Canada, the Hamersley-Nabberu basins of Western Australia and the Bababudan basin of southern India. Jagannathpur and Malangoti volcanics are weakly metamorphosed tholeiites that are believed to be younger.

(4) The North Singhbhum orogen commences with a basal conglomerate on Singhbhum granite and exposes a progressively younger succession towards the north. Low-grade metasediments overlie the basal conglomerate. The major Singhbhum shear zone occurring further north is believed to have not disrupted the stratigraphy, although some authors feel that the shear zone could be a stratigraphic boundary. The shear zone is followed to the north by the flyschoid sediments of Singhbhum Group consisting of the Chaibasa and Dhalbhum Formations of Saha et al. (1988). The spine of the orogen is marked by the Dalma volcanic belt, which is followed to the north by a succession of fine clastics, cherts, felsic volcanics and mafic-ultramafic schists. These sediments belong to Singhbhum Group of Sarkar and Saha (1983) but may belong to a younger sequence (*see* Gupta and Basu, 2000) to be called Chandil Formation. Tamar-Poropahar (-Khatra) shear zone traverses these sediments close to the northern boundary of the orogen. The irregular, intrusive contact of the northern part of Chandil Formation with Chhotanagpur Gneiss is noticed further north of the shear zone. This contact zone marks the boundary of North Singhbhum orogen against the Satpura mobile belt that is represented here by the Chhotanagpur Gneiss.

(5) Dykes of Newer Dolerite traverse the entire craton and mark major episodes of cratonic stabilisation.

(6) The less deformed Kolhan basin, comparable to 'Purana' basins, unconformably overlies Singhbhum granite.

### Geophysical Studies

The Bouguer anomaly map of the craton shows several gravity highs and lows (Fig.3S-3a). Gravity highs are associated with supracrustals and mafic-ultramafic complexes. Gravity lows are associated with granites. The gravity anomalies show a range of –35 to –40 mGals. The estimated thickness of the

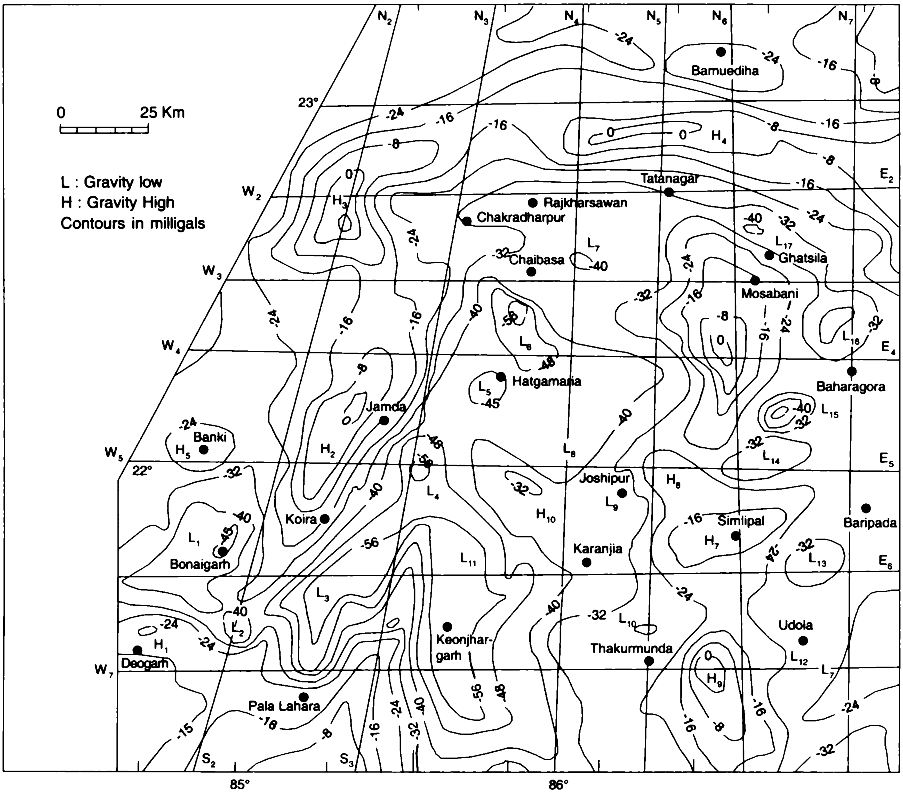

0 25 Km
L : Gravity low
H : Gravity High
Contours in milligals
23°
22°
85°
86°
Bamuediha
Tatanagar
Rajkharsawan
Chakradharpur
Chaibasa
Ghatsila
Mosabani
Baharagora
Hatgamaria
Jamda
Banki
Joshipur
Simlipal
Baripada
Koira
Bonaigarh
Karanjia
Keonjhargarh
Thakurmunda
Udola
Deogarh
Pala Lahara
N2
N3
N4
N5
N6
N7
W2
W3
W4
W5
W7
E2
E4
E5
E6
S2
S3

Fig.3S-3a. Bouguer anomaly map of Singhbhum and adjoining areas (from Saha, 1994).

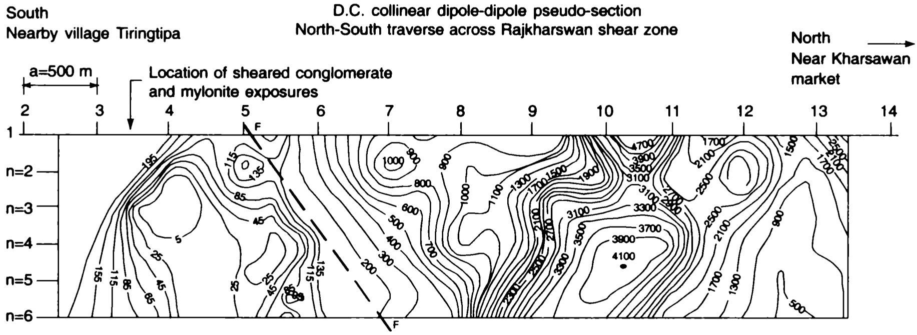


Fig.3S-3b. Resistivity profile across Singhbhum shear zone (from Saha, 1994).

supracrustals ranges between 5 and 7.5 km. Gravity estimates provide a crustal thickness of 33-34 km under Singhbhum granite, whereas electrical conductivity measurements suggest a thickness range of 23-42 km up to the Moho. Magnetotelluric estimates suggest an overall crustal thickness of 38 km.

In contrast to Singhbhum granite, the North Singhbhum orogen shows higher gravity anomalies (–15 to –20 mGals) with a high relief over Dalma volcanics. Continuation of sialic crust below the Singhbhum Group is visualised by deep resistivity studies. The Singhbhum shear zone (SSZ) and Tamar-Porapahar shear zone (TPSZ) demarcate high gravity fields.

Magnetic anomalies are of low amplitude over Singhbhum granite, medium amplitude on Chaibasa Formation, and of high amplitude over the magnetic Dhalbhum Formation. The Singhbhum shear zone is marked by a prominent magnetic lineament. Two cross linears near Jamshedpur (Tatanagar) are interpreted as basement features.

Sharp resistivity contrast between the SSZ and North Singhbhum orogen (NSO) is noticed (Fig.3S-3b). The 1 to 1.5 km wide shear zone has very low resistivity values, and the thrust zone dips north up to a depth of 2.5 km.

Heat flow measurements show uniform values of ~61mW/m$^2$ in Singhbhum shear zone, which is close to the global average. The higher than mean values for Precambrian in the shear zone may be attributable to radioactive mineralisation in the area.

**Previous Work**

The Singhbhum region has attracted geological attention from the early days of British power due to its proximity to the capital at Kolkata (Calcutta) and the rulers' desire to exploit the abundant coal resources of the region. Pioneering geological work by V. Ball in 1881 and by H.C. Jones and M.S. Krishnan in the nineteen thirties resulted in the division of supracrustals into Older Metamorphic Series and Iron Ore Series. Dunn (1942) and Dunn and Dey (1942) combined all the supracrustals into a single Iron Ore Series, followed by Dhanjori and Dalma lavas, and finally by the Kolhan Series and Newer Dolerite. Iyengar and Murthy (1982) divided the iron formation basins into the older Badampahar Group and the younger Koira Group, overlain by Simlipal Group (=Dhanjori Group) and underlain by Ghatsila Group (=Singhbhum Group). This was perhaps the first attempt to recognise Singhbhum granite as an ancient cratonic nucleus. Banerjee (1974) followed a similar stratigraphic scheme, but retained the Older Metamorphic Group as older than the older Iron Ore Cycle at Badampahar. He also included Gangpur Group as younger than the Kolhan Group. Sarkar and Saha (1983) and Saha et al. (1988) attempted a major revision of Singhbhum stratigraphy, including the identification of different phases of Singhbhum granite that were clubbed into three main age components. They identified the older supracrustals near Champua and called them the Older Metamorphic Group (OMG), which is intruded by Older Metamorphic Tonalite Gneiss (OMTG). The OMTG forming the earliest granitoid event occurs as mega xenoliths or giant enclaves in Singhbhum granite. Saha et al. (1988) included three iron formation basins under the Iron Ore

Group, succeeded by the Singhbhum Group occurring to the north of the Singhbhum shear zone in the North Singhbhum orogen. The volcanic basins were treated as a younger unit called the Dhanjori Group followed by the Kolhan Group and Newer Dolerite. Sinha et al. (1997) correlated the Iron Ore Group with Dhanjori Group on the basis of their basal uraniferous quartz pebble conglomerate horizon. Singhbhum Group, Kolhan Group and Newer Dolerite were placed as younger, as in the other classifications. Singh (1998) correlated the younger Iron Ore Group (=Koira Group) with Chaibasa Group (Singhbhum Group), underlain unconformably by the Dhanjori Group that overlies Singhbhum granite and enclaves of Older Iron Ore Group (=Badampahar Group) with an unconformity. Gupta and Basu (2000) believed in a continuously northward younging succession for the North Singhbhum Orogen from Singhbhum granite, uninterrupted by the Singhbhum shear zone. They opined that volcanics occupy different stratigraphic levels, within the sediments of Singhbhum Group. The stratigraphic problem is complicated by the similarity of lithologies (quartzite, phyllite and conglomerate interbeds) at the base of Dhanjori, Koira and Singhbhum Groups. These three groups occur as consecutively younger sequences with transitional contacts.

In all these classifications, the status of Singhbhum granite is variable, namely (i) basement to all supracrustals, (ii) basement to some parts and intrusive to other parts of the total succession or (iii) intrusive into all supracrustals. The supracrustals were also classified into different groups with contrasting order of superposition. The prominent intrusive suites of chromiferous ultramafics, gabbro-anorthosite-granophyre and 'soda'granite-granophyre are placed at different stratigraphic levels depending on individual predilections. Such controversies show that there are more questions than answers in Singhbhum stratigraphy. The various vicissitudes of stratigraphy are listed in the major schemes under Table 3S-1. The favoured classification in this book is comparable to the global secular models and to Dharwar stratigraphy. Dhanjori and Simlipal sequences are Neoarchaean (~2800 Ma) quartzite-basalt sequences like the lower part of the Bababudan Group; Koira Group is Fe-Mn cycle like the Vanivilas subgroup of Chitradurga Group; and the Singhbhum Group like the Ranibennur Subgroup of Chitradurga Group. OMG and Badampahar are like the older Sargur Group.

Recent reviews of Singhbhum geology are available in the books by Banerji (1982), Mukhopadhyay (1988), Saha (1994), Mahadevan (2002) and papers by Acharyya (1993), Mazumder (1996), Singh (1998, 2000), Bose (2000), Gupta and Basu (2000), Jena and Behera (2000), Sarkar (2001), Mukhopadhyay (2001) and Misra (2006). Geochronological data with emphasis on U-Pb and Pb-Pb zircon ages and Sm-Nd ages are summarised in Ghosh et al. (1996), Misra and Johnson (2005) and Misra (2006).

**Table 3S-1.** Regional Stratigraphy of the Singhbhum craton

| Dunn and Dey (1942) | Iyengar and Murthy (1982) | Sarkar and Saha (1983) and Saha et al. (1988) | Gupta and Basu (2000) (mainly North Singhbhum orogen) | Singh (1998) | Present Classification |
|---|---|---|---|---|---|
| Newer Dolerite | Dolerite | Newer Dolerite | Kuilapal granite | Kolhan Group | Newer Dolerite (different ages) |
| | Tamperkola granite | Majurbhanj granite | | | Kolhan Group (= Kunjar, Gangpur Group?) |
| Kolhan Series | Gangpur Group | Gabbro-anorthosite-granophyre | | | 'Soda' granite, granophyre, Kuilapal granite |
| | | Ultramafics | | | Jagannathpur, Malangtoli Volcanics |
| | | Kolhan Group | Dalma Group | Dalma Group | Dalma Group |
| Unconformity | Unconformity | Unconformity | | Mayurbhanj granite | |
| | | | Singhbhum Group | | Singhbhum Group |
| Soda granite, granophyre | Bonai Granite | | Singhbhum Shear Zone | | |
| | Koira Group | | | Younger Iron Ore Group= | Koira Group with Ongarbira Volcanics |
| | Unconformity | | | Chaibasa Group | |
| Singhbhum granite | Rompahari granite | Dhanjori Group | Dhanjori Group (including Iron Ore Group of Noamundi-Koira) | | Dhanjori Group (= Simlipal Group) |
| | Soda granite, granophyre | Singhbhum Group | | | |
| | Gabbro-anorthosite-granophyre | | | | |
| Dalma and Dhanjori lavas | Chromiferous ultramafics | | | | |
| | Simlipal Group | | | | |
| Unconformity | | Unconformity | Unconformity | | Unconformity |
| | | Singhbhum Granite (SG-B) | | | |
| Iron Ore Stage | Ghatsila Group | Iron Ore Group | | | SBG-B, Bonai granite, Chakradharpur granite, Tamperkola granite, Mayurbhanj granite |
| | Unconformity | Singhbhum Granite (SG-A) and Nilgiri, Bonai, Chakradharpur granite | | | |
| Chaibasa Stage | Badampahar Group | | | | Badampahar Group (=Gorumahisani Group) |
| | | Older Metamorphic Tonalite Gneiss | OMTG and Singhbhum Granite | OMTG/SBG-A Chakradharpur granite | OMTG/SBG-A/ Kaptipada granite and parts of Bonai and Chakradharpur granites |
| | Singhbhum Granite basement | Older Metamorphic Group | OMG and Badampahar Group | OMG | OMG |
| | | | | Basement not exposed | Base not recognised |

## OLDER SUCCESSIONS AND GRANITOIDS

### Older Metamorphic Group

The Older Metamorphic Group (OMG) occurs as a series of enclaves, the larger ones having dimensions of a few km$^2$. The type area of OMG is Champua (Fig.3S-2), where the enclaves cover an area of 200 km$^2$. OMG enclaves also occur near Shankarpur, Onlajodi (Aunlajorhi), Bahalda and Haludpukhur. Scattered amphibolite enclaves are spread all over Singhbhum granite. The main rock types of OMG are biotite-muscovite schist, quartzite and fuchsite quartzite, ortho-amphibolite, banded para-amphibolite and schistose iron formation. Komatiites, characteristic of the ancient supracrustals/ greenstones of the world, are conspicuously absent in the OMG. Regional foliation trends vary from ENE to WNW, with steep dips ro N or S. The first fold is tight to isoclinal with steep NE plunge. A pronounced reclined fold with ENE plunge is seen near Champua. The first folds are affected by later SE plunging folds.

Pelitic schists rich in quartz (~50%), biotite, muscovite and rare garnet and sillimanite, with accessory zircon, sphene and rutile are fairly common. The accessory minerals indicate a sialic provenance. The pelites are enriched in Ni and Cr and poor in Ti, like most of the Archaean pelites. Fuchsite quartzites grading into quartz-muscovite schists are also common. The ortho-amphibolites are predominantly massive and schistose with hornblende and calcic plagioclase as essential constituents, and subordinate amounts of clinopyroxene, epidote, sphene and opaques. The amphibolites are enriched in LILE and range in composition from basalts to basaltic andesites of tholeiitic series. They may have originated by partial melting of spinel lherzolite followed by fractionation of olivine tholeiite magma. Crustal contamination or AFC (assimilation fractional crystallisation) is probably important in their genesis. The banded calc-silicate amphibolites (para-amphibolites) have dark bands rich in hornblende and light bands consisting of diopside, epidote, zoisite and calcite. They are believed to have formed by the weathering of mafic rocks. Iron formation is not widespread, but when present, consists of quartz, magnetite and cummingtonite-grunerite. P-T conditions deduced from mineral assemblages are 600-650°C and 5-5.5kb, which are similar to modern geotherms. Sm-Nd (WR) isochron of OMG amphibolite yields an age of 3300 Ma, corresponding to $^{40}Ar/^{39}Ar$ plateau ages. Pb-Pb WR age is 3380 Ma and Rb-Sr age is 3280 Ma. A cluster of *in situ* Pb-Pb zircon ages is seen around 3550 Ma that may indicate either the depositional or provenance age.

## Badampahar Group

Iyengar and Murthy (1982) called the iron ore basin of the northeast as Badampahar Group. Other authors call it as Gorumahisani Group.

Badampahar belt is 120 km long with a maximum width of 10 km and extends from Rajnagar to Jashipur. The belt extends in a NNE to NW direction with bifurcated projections that jut into gneisses and break up into xenoliths. A small parallel belt (20 x 1-2 km) occurs to the west of the main belt, extending from Bhadra to Raipada. Tight folds plunging NNE are very common. There is a "structural unity" between the enclaves, coherent belts and the enclosing gneisses. Metamorphism ranges from lower to upper amphibolite facies resulting in quartzo-felspathic veining in the contact zones with the gneisses.

The dominant rock type is metabasalt, which is locally pillowed and amygdular, and is associated with agglomerates and tuffs. Metabasalts grade into amphibolites at the belt margins. The basalts are essentially olivine tholeiites ranging in composition from picrite through basalt to basaltic andesite. The volcanics have enrichment of Ni and Cr, along with depletion of LREE and LILE. Ultramafic volcanics ranging from peridotitic to basaltic komatiites, some of them with spinifex texture, are also important in this belt. These are $Al_2O_3$ depleted varieties showing fractionation of clinopyroxene. The ultramafics are mainly serpentinites, metapyroxenites and talc-tremolites schists. Those with very high Mg numbers are possibly cumulates or sills. Felsic volcanics form narrow and conformable lenses and are locally tuffaceous and felspar phyric. BIF of oxide and silicate facies is prominent within the metabasaltic association. Fuchsite quartzites and banded calc-silicate rocks are subordinate. Badampahar Group is intruded by 3100 Ma old granite that is equivalent of SB-G.

In the Daitari, Deogarh and Malayagiri areas, the southern Iron Ore Group yields SHRIMP U-Pb age of ~ 3.5 Ga (Sarkar and Saha, 1983). The dominant rock types are mafic-ultramafic rocks, BIF, metapelites, quartzites and calcareous sediments. The chromiferous ultramafic body of Sukinda-Nausahi is sandwiched between basaltic flows. The Malayagiri quartzite band is highly folded and is locally conglomeratic with clasts of jasper, chert and quartz. Andalusite schists are reported to be associated with the quartzites. The volcanics of Daitari area are high-Mg basalts at the base, followed by siliceous high-Mg basalts (SHMB) showing variolitic and plagioclase phyric textures, and finally capped by felsic volcanics and tuffs. Part of the lithological ensemble at Daitari is similar to that of Gorumahisani, but for the abundance of sediments (Dhanjori Group?) in the Daitari area. These rocks of *Daitari Group* are correlated with the Badampahar Group.

The enclave suite near Champua and the coherent belts of Badampahar-Gorumahisani and Daitari are equated stratigraphically by some authors (Acharyya, 1993) which is supported by the presence of continuous trail of enclaves from Badampahar belt through Jashipur and Raipada to Shankarpur near Champua (Jena and Behera, 2000). But the gross lithologies of the belts are different and Badampahar belt may be younger than OMG (Singh, 1998). In Daitari area also, more than one succession is noticed (Acharya, 2002), and there is need for further mapping to delineate the different sequences.

## Older Metamorphic Tonalite Gneiss (OMTG)

The OMTG occupies an area of about 900 sq. km and occurs as mega-xenoliths within the vast Singhbhum granite, near Champua, Seraikala, Onlajodi, Rairangpur and Thakurmunda, where they extensively intrude the OMG. The structural concordance between OMG and OMTG shows their syn-kinematic development.

The OMTG is predominantly of tonalite-trondhjemite-granodiorite (TTG) composition, with subordinate granodiorite, quartz diorite and monzodiorite. The gneisses are well foliated and locally banded, and contain plagioclase, quartz, biotite and subordinate K-felspar, with accessory zircon, sphene and apatite. Garnet is rare. In overall composition, they are comparable to the Archaean TTGs of the world. The gneisses show high Sr, low Ba/Sr ratio and variable K/Rb. They are moderately enriched in LREE with a steeply sloping pattern without Eu anomaly. They may have been formed by 40% partial melting of OMG-type ortho-amphibolites at 590-770°C and 5kb, corresponding to depths of 17-18 km.

The gneisses define a Pb-Pb isochron of 3378±98 Ma and 3405±53 Ma, along with Sm-Nd age of ~3.29 Ga and Rb-Sr isochron of 3280±130Ma. *In situ* Pb-Pb zircon age and U-Pb TIMS zircon age cluster around ~3.45 Ga. Older ages of about 3600-3800 Ma that were initially obtained, were retracted through later studies. The age of these gneisses can therefore be bracketed between 3300 and 3450 Ma. The OMG, together with OMTG, were probably involved in a widespread later metamorphic event at 3100-3200 Ma.

## Singhbhum Granite

The N-S elongated, oval shaped Singhbhum granite complex is divided for the most part into twelve units by A.K. Saha and his co-workers (Saha, 1994), on the basis of (i) mutual intrusive relations, (ii) older granitic units as enclaves in younger units, (iii) truncation of magmatic foliation and banding of one unit by the other, and (iv) presence of rows of enclaves between different units. All these units are characterised by steeply dipping primary foliation and rhythmic banding. Xenoliths of tonalitic gneisses, migmatites and mafic-ultramafic rocks abound in all the units, although some units are richer in xenoliths. On the basis of field relations, petrography and geochemistry, particularly the REE data, the twelve granitic units are classified into three successive and closely related phases of emplacement (Fig.3S-2). Phase I is a relatively K-poor granodiorite-trondhjemite. Phases II and III are granodiorite grading into adamellite. Phase III includes a substantial area of Singhbhum granite.

In terms of major and trace elements and REE, the Phases I and II belong to a distinct population. The Phases I and II are therefore combined into Type A (SG-A) and Phase III into Type B (SG-B). Type A shows gentle slope for REE with slightly depleted HREE and no Eu anomaly. Type B shows LREE fractionation, with flat HREE and moderate Eu anomaly. SG-A granite contains enclaves of OMG/Badampahar amphibolites and these may be protoliths for SG-A. Petrogenetic calculations show that ~20% partial melting of OMG-type amphibolite may generate granitic magmas from which SG-A may form by differentiation. Similar modelling suggests that SG-B may develop by 30% partial melting of low-K andesite protolith and progressive crystallisation up to ~50% may give rise to the granite. The REE patterns of the three phases are given in Figs.3S-4a,b,c.

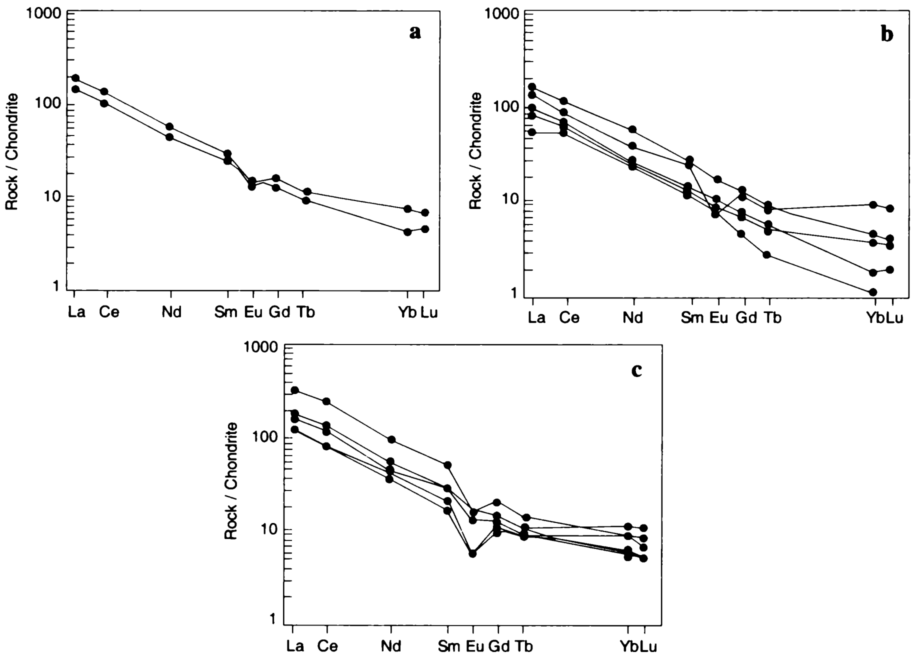


**Fig.3S-4.** REE patterns of Singhbhum granite (**a,b**) SBG-A.and (**c**) SBG-B (after Mukhopadhyay, 2001).

Folded gneissic banding within the OMTG xenoliths, truncated by the foliation of Singhbhum granite (SG-A), indicates that OMG/Badampahar Group together with OMTG were deformed and metamorphosed before the emplacement of the granite SG-A. Despite the SG-A and OMTG having similar range of ages (3300-3400Ma) and REE patterns, the field evidence supports the antiquity of OMTG.

Pb-Pb, Sm-Nd and Rb-Sr isotopic systematics indicate that SG-A is about 3300-3400 Ma old, whereas SG-B that covers a wide area has an age of 3000-3100 Ma.

### Bonai Granite

Bonai granite occupies a triangular area of 700 $km^2$ and is separated from Singhbhum granite by the Koira Group. It is a predominantly porphyritic granite with small patches of migmatitic trondhjemite and older supracrustal enclaves. The granite consists of plagioclase megacrysts ($An_{10-25}$), K-felspar, quartz, biotite and muscovite. The main body of granite is about 3100 Ma old, similar to SG-B, whereas the xenolithic trondhjemite is dated at 3300 Ma like the SG-A.

The xenolithic trondhjemite has LREE enriched pattern with no Eu anomaly. The host granitoids have flat HREE pattern with negative Eu anomaly. The migmatitic xenoliths were produced by heterogeneous mixing of two varieties of trondhjemite derived by the partial melting of garnet amphibolite. The main granite pluton is produced by the partial melting of older high $Al_2O_3$ trondhjemite. Equigranular trondhjemite forms the next important component of Bonai granite.

### Kaptipada Granite

Saha (1994) described the southeastern part of Singhbhum granite as Nilgiri granite and differentiated it into several varieties. Since the granite exposed in Nilgiri hills belongs to a younger suite, the name Kaptipada granite is preferred by most workers. Younger supracrustal and intrusive rocks surround the granite. Kaptipada granite abounds in xenoliths of migmatite and amphibolite, like the Singhbhum and Bonai granites. The dominant composition of the pluton is high $Al_2O_3$ trondhjemite-granodiorite. The pluton has a fractionated REE pattern without Eu anomaly and is thought to have been derived by partial melting of amphibolite. Granite-diorite forms the youngest component of the pluton. There is a broad similarity in the geochemistry of Kaptipada granite and Singhbhum granite type A (SG-A).

The granite is bounded to the south by a ridge of gabbro-anorthosite and granophyre, followed by hornblende granite and a shear zone. Tonalite juts out of alluvium further south of the hornblende granite. Rb-Sr, Pb-Pb and Sm-Nd isochrons of the granite suggest two groups of ages of 3300 Ma and 3000-3100 Ma corresponding to the ages of Singhbhum granite.

### Pala Lahara Gneiss

The southwestern part of Singhbhum granite is marked by the undifferentiated Pala Lahara (Pallahara) gneiss (Fig.3S-2), which has distinctive gneissic banding with dark bands of hornblende and magnetite alternating with white quatzofelspathic bands. The gneiss has an overall compositional range of normal granite grading into granodiorite. The Pala Lahara and Deogarh iron formation sub-basins (part of Daitari basin), correlated with Badampahar Group, are concordantly deformed with this gneiss. The gneiss has not been isotopically dated so far.

## YOUNGER IRON ORE SEQUENCE

### Koira Group

Saha et al. (1988) considered the prominent iron formation basin of the western Singhbhum-Keonjhar region as the main area of Iron Ore Group. Iron ore basins of Gorumahisani-Badampahar in the east and Daitari in the south, originally considered to belong to Iron Ore Group by Saha et al. (1988), have now been classified under the older Badampahar Group. The main differences between the eastern (Badampahar) and western (Noamundi-Koira) iron ore basins are the following:(i) magnetite-rich BIFs are less well-developed in the east than in the west; (ii) BIF is underlain by manganese horizons in the west, along with carbonate rocks, whereas those are absent in the eastern basin denoting significant facies change; (iii) sedimentary structures like ripple marks, cross-bedding and scour and fill structures are well developed in the western basin and are absent in the east; (iv) primitive biogenic forms are seen in the west whereas they are absent in the east; and (v) peridotitic komatiites with spinifex textures are well developed in the east, whereas they are absent in the west. These significant differences indicate that the eastern belts have an oceanic affinity (ultramafics-mafics-BIF), whereas the western basin has a continental platform character. There are no compelling evidences to believe that these two different facies are homotaxial. The eastern basin (Badampahar Group) is considered as equivalent to or younger than OMG, and the western basin (Koira Group) as equivalent to the Iron Ore Group of Sarkar and Saha (1983) and is younger than Badampahar Group. In order to conform to the recent stratigraphic codes, the name Koira Group suggested by Murty and Acharya (1975) and adopted by Iyengar and Murthy (1982) is retained. Banerjee (1974) called this unit as the Noamundi-Porhat Iron Ore Group.

Koira Group comprises five formations with a basal polymict conglomerate overlain by a sequence of quartz arenite and shale, with local dolomite and BIF. The sequence is intruded by gabbro and dolerite. Sedimentary structures like compositional banding, ripple marks, current bedding, scour and fill, micro-desiccation features etc. indicate deposition proximal to shoreline. The mineralogy of kaolinite and illite in shales and their geochemistry (especially the Ca/Mg ratio) points to fresh water lacustrine environment. The overall picture is therefore of continental margin environment.

Koira Group overlies the OMG of Champua to the east and the Bonai granite to the west (Figs.3S-2 and 3S-7). It is believed to be intruded by the Singhbhum granite (SG-B) as evidenced by BIF enclaves in Deo River section. This interpretation is controversial since the BIF could as well belong to Badampahar Group. If the intrusion by SG-B granite is confirmed through later work, Koira Group may be placed between the two phases of Singhbhum granite (SG-A and SG-B) i.e., between 3300 and 3100 Ma (*see* Misra, 2006).

The overlying sequence to the north and west of Koira Group has a controversial status. The sequence consists of several bands of orthoquartzite with minor arkose and conglomerate, overlain by a thick sequence of phyllite interspersed with minor volcanics. Sarkar and Saha (1983) regard it as part of Singhbhum Group, separated from Iron Ore Group of Koira basin by Singhbhum shear zone. Some others call it as Bonai Group having faulted contact with Koira Group. Still others equate it with the Dhanjori Group overlying the Singhbhum granite unconformably to the south of the Singhbhum shear zone. This succession may correlate with Singhbhum Group as it forms a rim around Singhbhum granite, and constitutes a younger succession above Koira Group, separated by a disconformity. It overlies the basal sedimentary sequence of Dhanjori Group. Singhbhum Group is described under the North Singhbhum orogen.

## GABBRO-ANORTHOSITE SUITE

A distinct suite of gabbro-anorthosite occurs along the eastern margin of the Singhbhum craton (Fig.3S-5), extending in a linear, discontinuous belt from Butgora to Nausahi. A prominent intrusion is seen near Gorumahisani. The gabbros grade into ultramafic rocks like picrite, lherzolite and pyroxenite that are metamorphosed to serpentinites and talc-tremolite-chlorite schists. The gabbros also grade into anorthosites, which are locally pegmatitic. At places, the intrusions host veins and segregations of titaniferous and

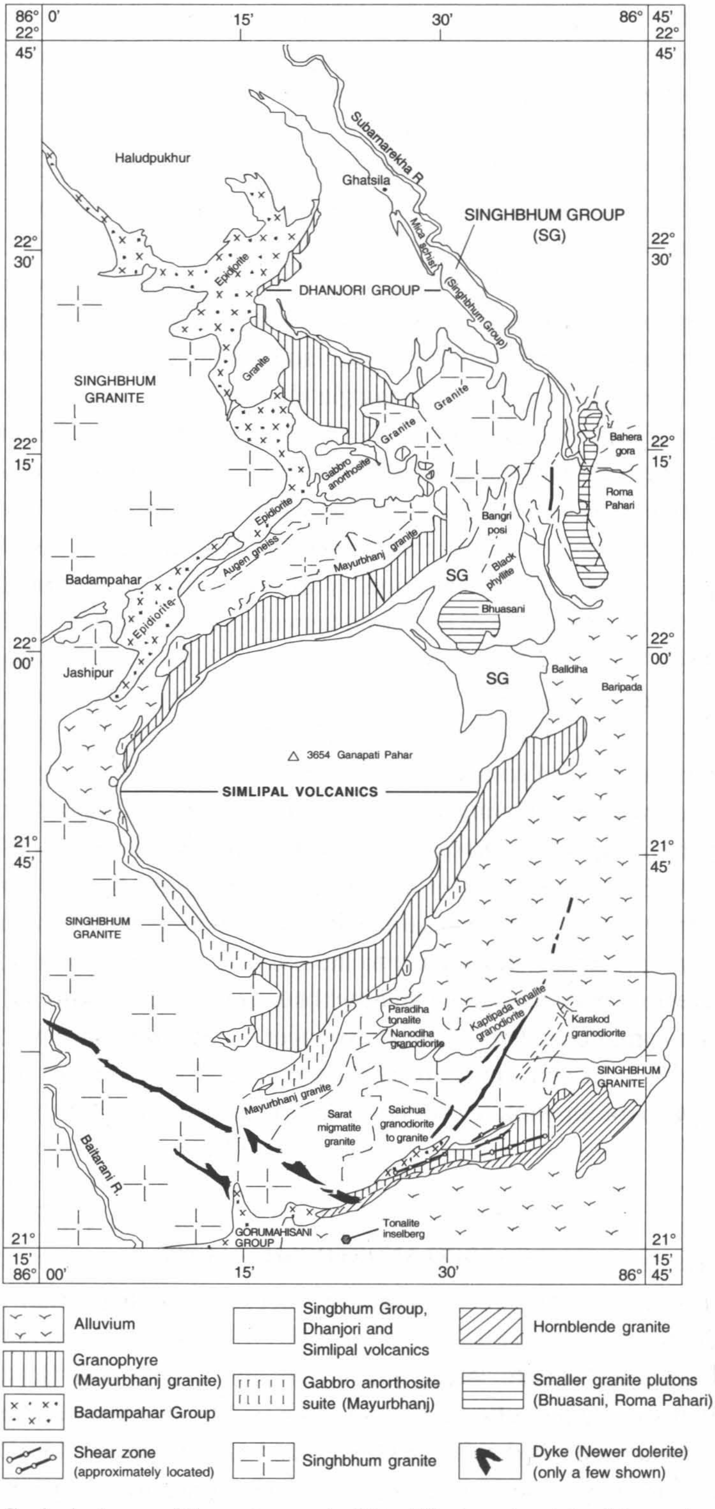

86° 0'
15'
30'
86° 45'
22° 45'
22° 30'
22° 15'
22° 00'
21° 45'
21° 15'
86° 00'
Subarnarekha R.
Ghatsila
Haludpukhur
Mica schist (Singhbhum Group)
SINGHBHUM GROUP (SG)
Epidiorite
DHANJORI GROUP
Granite
SINGHBHUM GRANITE
Gabbro anorthosite
Bahera gora
Roma Pahari
Bangri posi
Black phyllite
Augen gneiss
Mayurbhanj granite
Badampahar
SG
Bhuasani
Jashipur
Balidiha
Baripada
3654 Ganapati Pahar
SIMLIPAL VOLCANICS
Paradiha tonalite
Nanodiha granodiorite
Kaptipada tonalite granodiorite
Karakod granodiorite
Sarat migmatite granite
Saichua granodiorite to granite
Baitarani R.
GORUMAHISANI GROUP
Tonalite inselberg
Alluvium
Granophyre (Mayurbhanj granite)
Badampahar Group
Shear zone (approximately located)
Singbhum Group, Dhanjori and Simlipal volcanics
Gabbro anorthosite suite (Mayurbhanj)
Singhbhum granite
Hornblende granite
Smaller granite plutons (Bhuasani, Roma Pahari)
Dyke (Newer dolerite) (only a few shown)

**Fig.3S-5.** Geological map of the eastern part of Singhbhum craton (after Mazumder, 1996).

vanadiferous magnetite, as at Dublabera, Kativar Pahar, Gorumahisani, Baula and Nausahi.

The gabbro-anorthosite suite is associated with granophyre in many areas. Their mutual relation has been controversial, and they are interpreted either as comagmatic bodies or separate intrusions. Several evidences such as intrusion of granophyre into gabbro, presence of gabbro enclaves in granophyre and the big compositional gap between gabbro and granophyre suggest that gabbro is older than granophyre. This is evident in the relationship between the gabbro-anorthosite and granite-granophyre of Mayurbhanj. The Mayurbhanj granite-granophyre is dated by Pb-Pb zircon at 3100 Ma, although its Rb-Sr age is much younger at ~2200 Ma. The gabbro-anorthosite body near Udal underlies the outlier of Dhanjori basin and is therefore older than Dhanjori Group.

The chromiferous ultramafics of Jojahatu, Sukinda and Baula-Nausahi are regarded as older than the Simlipal (Dhanjori) Group. The Baula-Nausahi ultramafics are possibly connected to those of Kunderkocha (Gorumahisani) through a train of enclaves in Singhbhum granite. The Baula-Nausahi body is noted for PGE (Platinoid Group Elements) mineralisation. Jojahatu and Sukinda ultramafic bodies are known for chromite mineralisation. Jojahatu-Roro body hosts chrysotile asbestos.

## VOLCANIC SUCCESSIONS

Archaean to Early Proterozoic volcanic basins occur discontinuously all along the periphery of Singhbhum granite(Figs.3S-1,2). Prominent among them from the east to west are Simlipal, Dhanjori, Dalma, Ongarbira, Jagannathpur (Dungoaposi) and Malangtoli (Nuakot). Simlipal and Dhanjori belong to Dhanjori Group, Dalma overlies Singhbhum Group, Ongarbira overlies Koira Group, and Jagannathpur and Malangotli overlie Singhbhum granite. Their mutual relationship with the surrounding rocks has, however, been controversial and consequently there is no consensus on their stratigraphic correlation. The volcano-sedimentary basins are therefore described together in this section.

### Simlipal Basin

A large oval-shaped basin (150 x 60 km) starting with a basal quartz pebble conglomerate (QPC), orthoquartzite and feldspathic quartzite overlies the Singhbhum and Kaptipada granites and Badampahar Group. The surrounding sediments are correlated with Koira Group, Singhbhum Group or lower part of Dhanjori Group by various workers. Mayurbhanj gabbro-anorthosite and Mayurbhanj granite-granophyre are believed to intrude the basin at its flanks.

The basal conglomerate-quartzite unit is overlain by three bands of spilitic basalts and associated tuffs, alternating with bands of cross bedded orthoquartzite. Volcanic breccias at the base of the flows give place to tuffs and tufffaceous sediments at the top. The volcanics are amygdular and variolitic. They range in composition from tholeiitic basalt to basaltic andesite. They show appreciable REE fractionation and significant LREE enrichment having $(Ca/Yb)_N$ ~7 and $(La/Sm)_N$ ~2.5.

At the centre of the basin occurs a differentiated sill having a thickness of 800 m called Amjhor (Amjori) sill. The sill has dunite at the base followed upward by peridotite, picrite, gabbro and quartz diorite. The chilled facies, possibly indicating the initial magma, is a high-Mg tholeiite with Mg no. ~58, and $CaO/Al_2O_3$= 0.53. The sill shows REE fractionation and LREE enrichment with $(Ce/Yb)_N$=3.

There is a suggestion that the Simlipal basin may be a crypto-explosion structure or astrobleme, based on explosive volcanism and inward dips, but no impact structures are reported so far. The intrusive Mayurbhanj granite-granophyre gives a wide range of ages (3100-2200 Ma) that do not help to constrain the upper age limit of Simlipal Group, although by comparison with Dhanjori basin the Simlipal Group may have an age of ~2800 Ma.

### Dhanjori Basin

The northwest trending elongate Dhanjori basin with gentle inward dips in the west and south, is intensely folded into west-verging symmetrical folds in the eastern margin close to the Singhbhum thrust. The succession has marked similarities with the less deformed Simlipal basin in the south, and therefore Dhanjori and Simlipal Groups are correlated with each other. The lithologies of Dhanjori basin overlie the Badampahar Group and Singhbhum granite. The surrounding sediments are correlated with the Singhbhum Group on the basis of a conglomerate in Jaduguda uranium mines that is separated from the underlying basal Dhanjori conglomerate (equated with basal QPC of Koira Group) by a significant thickness of sediments of Singhbhum Group (Sinha et al. 1997). Others regard these sediments as either older or younger than the Dhanjori Group. Gupta et al (1985) divide Dhanjori Group into two formations (informally called the lower and upper). The lower formation consists of a pebbly phyllite, with minor mafic-ultramafic intrusions. The upper formation starts with arkose, conglomerate and phyllite that pass upwards into a dominantly volcanic association. The volcanics are correlated with Dalma lavas by some authors, whereas others consider Dalma Group as younger than Dhanjori Group.

The Dhanjori lavas are predominantly basalts and basaltic andesites of tholeiite series. Picrites are subordinate. They show moderate to strong REE fractionation with $(Ce/Yb)_N$=3 to 5, moderate LREE enrichment, $(La/Sm)_N$ ratio ranging from 2 to 3 and poor HREE fractionation. Dhanjori volcanics yield Pb-Pb and Sm-Nd isochron ages of 2820 and 2790 Ma (i.e. ~2800 Ma) with large error bars. The uncertainty associated with such ages needs to be overcome by further dating.

### Dalma Volcanics

Dalma volcanics occur in an arcuate belt 200 km long and 3-7 km wide along the spine of the North Singhbhum orogen. The volcanics are folded into a large syncline with an axial ($F_2$) surface trending E-W. Northern limb of the syncline is overturned to the south and is bound by a thrust called the Dalma thrust. The syncline is refolded on its eastern and western ends. The eastern end is marked by large-scale $F_3$ folds on NE-SW axis. Reclined $F_1$ folds are seen at both ends of the belt.

Dalma Group of volcanics is divided informally into lower and upper formations. The lower formation overlying the Chaibasa Formation of the Singhbhum Group, consists of carbon phyllite, tuff and quartzite interlayered with volcanics. Reworked pyroclastic conglomerate indicates a minor break in deposition between the lower and upper formations. The upper formation is represented by extensive development of high-Mg (picritic to komatiitic) volcaniclastics and komatiites, along with co-magmatic intrusions. The ultramafics are amygdular and consist of actinolite-tremolite, chlorite, talc, carbonate and rare plagioclase. The basic volcanics that abound in the upper formation are agglomeratic and pillowed. The lavas are low-K and high-Fe tholeiites. The agglomeratic and breccia zone in the Dalma hill may mark a centre of eruption. The Dalma lavas also have contemporaneous weathering products like clays, which are metamorphosed to chloritic phyllites. The agglomerates and tuffs vary from subaerial proximal vent to subaqueous distal facies.All the Dalma rocks are metamorphosed in greenschist facies.

Ultramafic lavas have MgO>20% and Mg# ranging from 81 to 87. They range in composition from peridotitic to pyroxenitic komatiites, as well as picrites. They are characterised by low $Al_2O_3$, low incompatible element abundances (Zr, Y, Ti, P, Sr and Ba), high Ni and Cr, and have LREE depleted patterns with $(Ce/Yb)_N$=0.6. Some of the lavas are highly siliceous and are similar to SHMB (Siliceous High Magnesian Basalts) and boninites.

Dalma basalts are evolved tholeiites with Mg Nos. ranging from 41 to 64. Most are LREE depleted with $(Ce/Yb)_N$ ranging from 0.55 to 0.99. Consanguinity of Dalma ultramafic and mafic lavas implies their derivation from similar sources. Dalma volcanics are sometimes described as greenstone belt volcanics, or as ophiolites.

Due to overprinting by many events in the North Singhbhum orogen, the eruption age of the Dalma lavas could not be ascertained with certainty, although a broad lithological correlation with Dhanjori and Simlipal lavas has been suggested in literature. It is equally possible that the Dalma lavas are younger than the Dhanjori lavas. The oldest age known for Dalma lavas so far is the Rb-Sr, WR and mineral isochron of 2477±110 Ma, that is improved by exclusion of outliers to 2396±110 Ma.

### Ongarbira Volcanics

Ongarbira volcanics constitute an E-W trending, 40 km long, linear body with a hook-shaped synclinal closure at the eastern end. The syncline is interpreted as the first fold ($F_1$) with E-W axial plane having variable plunge. The volcanics comprise low-K tholeiites, ultramafic flows, tuffs, cherty felsic lavas and gabbro-pyroxenite intrusives. The volcanics show prominent pillow structures and pahoehoe toes. They are bound on either side by phyllites belonging to Koira Group. There is, however, a controversy as to whether it belongs to the lower part of Dhanjori Group or is an independent stratigraphic unit (Shaheba Group of Banerji, 1982). The volcanics are bound by faults, which may be related to movement on Singhbhum shear zone.

The ultramafic lavas are picritic and composed of tremolite-actinolite, chlorite, epidote, albite and rare serpentinised olivine. The metabasalts are tholeiitic and composed of actinolite, chlorite, epidote, plagioclase and quartz with rare relict augite. Locally the lavas are variolitic. There are two chemical types of basalts, one with LREE/LILE depleted MORB-type, and the other LREE/LILE enriched Fe tholeiite. The felsic volcanics associated with the mafic lavas are alkali trachytes. These volcanics are geochemically interpreted either as marginal basin basalts or as arc tholeiites by different authors.

### Jagannathpur (Dungoaposi) Volcanics

Basic volcanics covering 250 sq. km in the area east of Noamundi are called Jagannathpur or Dungoaposi lavas. Recent studies indicate them to be younger than Singhbhum granite and Koira Group but older than Kolhan Group. They yield an age of ~2250 Ma by whole rock Pb-Pb method. Earlier workers have correlated them with Dalma and Dhanjori volcanics. Jagannathpur lavas occur in gentle domes and basins with low dips of 15 to 20°SW. About 30 flows have been recognised. They are generally weakly metamorphosed komatiitic and tholeiitic metabasalts with minor basaltic andesites and basanites, thus covering a wide spectrum of compositions. Some have high MgO, low Ti/Zr and high Zr/Y resembling boninites. The lavas have a wide range of plagioclase compositions with augite as the chief pyroxene. Minor phases are opaque ores and interstitial micro-pegmatite.

### Malangtoli (Nuakot) Volcanics

Mafic lavas of generally flat-lying disposition and covering 800 sq. km in the area west of Keonjhar have a faulted contact with the BIF-associated lavas of Daitari Group in Gandhamardhan hills. They are probably homotaxial with Jagannathpur lavas and range in composition from basalts to basaltic andesites and belong to tholeiite series transitional to calc-alkaline series. They are feebly metamorphosed, having partly altered plagioclase and augite with subordinate orthopyroxene. In the inter-element diagrams, they show a spiked pattern with Sr, P and Ti anomalies indicative of crustal contamination or source enrichment.

## NORTH SINGHBHUM OROGEN

The North Singhbhum orogen (Fig.3S-6), about 50-60 km wide, exposes folded sequences in a number of sub-basins. The orogen is bounded in the north by the Chhotanagpur Gneiss and in the south by the Singhbhum granitic basement. The lithological succession shows normal order of superposition from the basement granite to the south to the gneisses at the northern margin, denoting a northerly younging trend. Dalma volcanic belt divides the orogen into two major segments.

A prominent ductile shear zone, known as Singhbhum shear zone, passes close to the southern margin of the orogen. The shear zone is well known for its copper-uranium, apatite-magnetite, and tungsten mineralisation. The northern margin of the orogen is marked by the less prominent Tamar-Poropahar(or South Purulia) shear zone of brittle-ductile type that hosts minor copper-uranium-lead mineralisation.

The orogen is divided into the following tectono-stratigraphic domains:

1. *Dhanjori domain*: This domain covers the area between Singhbhum granite (SG) and Singhbhum shear zone (SSZ) and constitutes the Marginal Zone of the orogen.
2. *Singhbhum shear zone*: The ductile shear zone extending from Porahat to Baharagora.
3. *Ghatsila domain*: The domain covers the area between Singhbhum shear zone and Dalma volcanics.

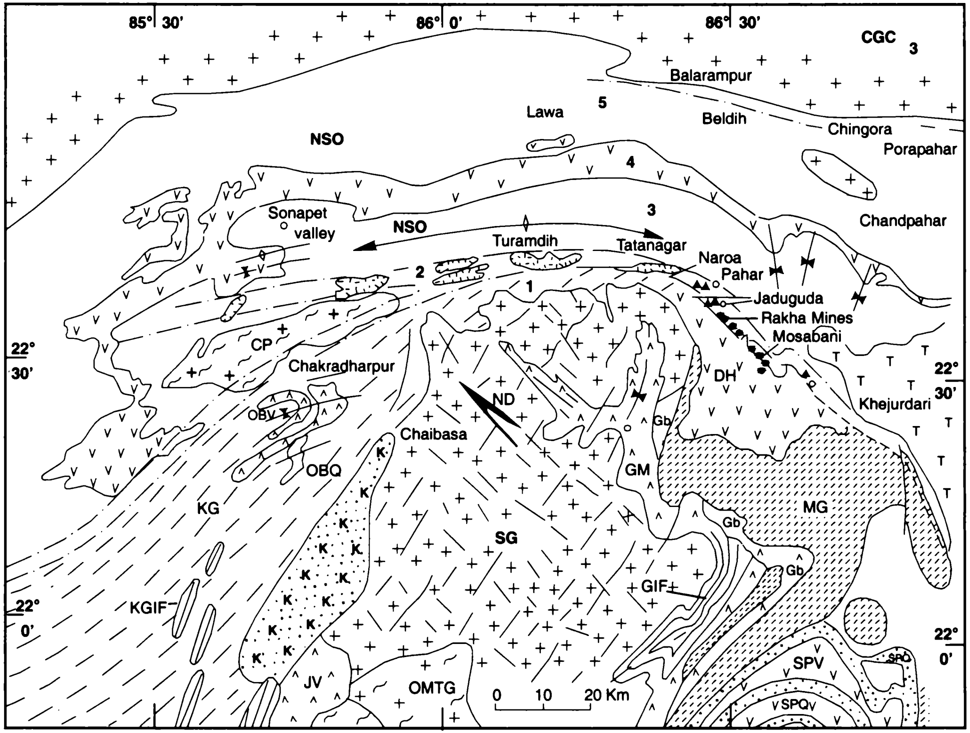

85° 30'
86° 0'
86° 30'
CGC
3
Balarampur
Lawa
5
Beldih
Chingora
Porapahar
NSO
4
Chandpahar
Sonapet valley
NSO
3
Turamdih
Tatanagar
Naroa Pahar
2
1
Jaduguda
Rakha Mines
Mosabani
CP
Chakradharpur
DH
Khejurdari
ND
OBV
Chaibasa
OBQ
Gb
GM
KG
MG
SG
Gb
Gb
KGIF
GIF
22° 30'
22° 0'
K
SPV
SPQ
JV
OMTG
0 10 20 Km
VSPQV
T

**Fig.3S-6.** North Singhbhum Orogen and adjoining areas (after Gupta and Basu, 2000). NSO- North Singhbhum Orogen. SG - Singhbhum granite. CGC - Chhotanagpur Gneiss. Domains of NSO: 1 - Dhanjori domain, 2 - Singhbhum shear zone, 3 - Ghatsila domain, 4 - Dalma volcanics, 5 - Chandil domain; KG- Koira Group, KGIF - Koira Group Iron Formation, OBV - Ongarbira volcanics, OBQ - Ongarbira quartzite, JV - Jagannathpur volcanics, CP - Chakradharpur granite, DH - Dhanjori volcanics, MG - Mayurbhanj granite - granophyre, Gb - Mayurbhanj gabbro, SPV - Simlipal volcanics, SPQ - Simlipal quartzite, GM - Gorumahisani volcanics, GIF - Gorumahisani iron formation, OMTG - Older Metamorphic Tonalite Gneiss, ND - Newer Dolerite, T - Phanerozoic gravels, K - Kolhan Group.

4. *Dalma volcanics*: Folded volcanic-pyroclastic assemblage.
5. *Chandil domain*: This domain covers the area between Dalma volcanics and Chhotanagpur Gneiss.

The Tamar-Poropahar shear zone (TPSZ) bounding the orogen to the north is described under Chapter 4 (Satpura mobile belt).

A brief description of these domains is given below:

### 1. Dhanjori Domain

Dhanjori domain represents the Marginal Zone between Singhbhum craton and North Singhbhum orogen, and commences with a basal polymict conglomerate resting on the basement of Singhbhum granite. Although the conglomerate is noticed intermittently all along the northern boundary of the Singhbhum granite, prominent outcrops are seen near Bisrampur and Damuth, where it is about 100 m thick. The polymict conglomerate contains pebbles of quartzite, chert, BIF, phyllite and greenish fuchsite quartzite, which resemble the lithologies of Older Metamorphic Group and/or Badampahar Group. This conglomerate has been interpreted as a product of submarine debris flows. In some sections, arkosic and lithic wacke marks the basement-cover interface, instead of the polymict conglomerate. In some other sections, phyllites overlie the migmatised and deformed basement granite, as seen near Saraikela.

The tongue of metasediments extending southward into the Singhbhum granite basement south of Tatanagar (Jamshedpur) has been interpreted as a cusp or keel within the granite, rather than as a roof pendant. There is no evidence here of Singhbhum granite intruding the cover sediments, and the enclaves in the granite belong to older supracrustal rocks. It is significant to note that the Newer Dolerite, which intrudes Singhbhum granite along with its enclaves, does not intrude the cover sediments. There are, however, minor instances of local remelting of the basement in some areas and of basement slices tectonically emplaced within the cover rocks. The basement-cover contacts are locally involved in shearing and mylonitisation.

The basal metasediments are overlain by grey and purple phyllites, quartzite, BIF and tuffaceous rocks along with ultramafic-mafic intrusives. Intraformational conglomerates are noted within this succession. Further west, this succession has gradational contact with the underlying Koira Group near Goikera. Dhanjori sediments represent variable environments from fluvial, lagoonal, beach to tidal flat deposits.

## 2. Singhbhum Shear Zone

The Singhbhum shear zone (also called the Copper Belt thrust zone) is a 1-10 km wide and over 200 km long arcuate belt extending from Baharagora in the east to Porahat in the west. Beyond Porahat it grades into a high angle fault and extends up to the western margin of Bonai granite. Another view is that the shear zone bifurcates with one arm wrapping round the northern margin of Chakradharpur granite (Fig.3S-6). Satellite imagery study shows that beyond Baharagora in the east, the arcuate southern continuation of the shear zone extends through Mayurbhanj to the Sukinda (or Kamakhyanagar) Thrust. The shear zone is characterised by extreme ductile shearing, multiple metasomatism, migmatisation and prominent mineralisation of Cu, U, tungsten and phosphate. It is not a single thrust plane, but made of several shear planes, which are cut across by a number of oblique strike-slip faults. The ductile shear zone consists of granite mylonite, quartz-mica phyllonite and quartz-tourmaline rock. The shear zone lithologies structurally overlie the Dhanjori and Koira metapelites, often with an intervening oligomictic sheared conglomerate. The shear zone rocks are in turn overlain by pelitic schists of Chaibasa Formation. There is a normal order of superposition in the lithological sequence on either side of the shear zone, without any depositional, structural or metamorphic break, but the transition zone is at places marked by kyanite quartzite. The bulk of the shear zone material is made of pelites and volcaniclastics, probably generated during the Dhanjori and Koira depositional cycles. The shear zone is characterised by the abundance of ultramafic intrusions such as hornblende schist, talc schist, serpentinite and a synkinematic body of serpentinised lherzolite with pyroxenite relics. The Singhbhum shear zone does not appear to be a major tectonic divide in the tectono-sedimentary evolution of the North Singhbhum orogen. Several detached felsic intrusive bodies like the Arkasani granite, granophyre, 'soda' granite and feldspathic schists produced by shearing occupy the shear zone.

The deformational history of this ductile shear zone is highly complex, marked by repeated phases of folding, mylonitisation and rotation of fabrics. Mylonitic foliation was developed initially along the axial plane of the first fold. This was repeatedly transposed with the development of successive mylonitic foliations parallel to the axial planes of later folds in the course of a single progressive deformation. It has been suggested that at least three sets of inclined to reclined and sinistral folds, and a late generation subhorizontal fold are developed during progressive deformation. It is also opined by some that the initial mylonitization was an early feature and therefore the major ductile shearing may date back to pre $D_1$-$F_1$ phase. The sense of shearing deduced from a host of shear sense indicators shows uniform reverse or north-side-up (up dip) movement during thrusting. This structural evolution has been explained in a kinematic model of N-S to NNE-SSW subhorizontal compression, superposed by strong shearing movement in the south and west.

The evolution of Singhbhum shear zone is multi-episodic (Misra, 2006) at 2200, 1800, 1600 and 1000 Ma. 'Soda' granite is emplaced at 2200 Ma; copper mineralisation occurred at 1800 Ma; Kuilapal granite intrusion and U-mineralisation at 1600 Ma; and final reactivation at 1000 Ma (Arkasani granite having Rb-Sr age of 1052±84 Ma, and K-Ar ages of micas).

### 3. Ghatsila Domain

This domain is characterised by an abundance of pelitic schists with bands of quartzite and amphibolite. Sarkar and Saha (1983) have named this succession as Singhbhum Group (2100-2300 Ma Rb-Sr and ~3100 Ma Pb-Pb), which is divided into a lower Chaibasa Formation and an upper Dhalbhum Formation, as shown below.

| | |
|---|---|
| Dhalbhum Formation (~4 km) | Phyllites with quartzite bands, andalusite-staurolite-chloritoid-chlorite-magnetite phyllites and basic sills |
| Chaibasa Formation (2-4 km) | Garnet-staurolite-kyanite mica schists with numerous bands of quartzite, ortho- and para amphibolites, and acid to basic tuffs |

The Chaibasa Formation is dominated by mica schists. Progressive metamorphic zonation of chlorite, biotite, garnet, staurolite, kyanite and sillimanite is seen towards the median axis of this domain. In the central part, such as near Kandra and Sonepat, the metamorphism is of Barrovian type. In the western part near Hesadih and the eastern part near Ghatsila and Galudih, low pressure metamorphism marked by the presence of andalusite and staurolite is manifest. The andalusite is interpreted as a product of either as pre- or syn-$D_1$ deformation. The metamorphic isograds themselves are regarded as folded by later deformational episodes.

Sedimentological studies of pelitic rocks interbedded with arenite bands have led to contrasting interpretation of depositional environments from various sectors of this domain. Cross stratification combined with penecontemporaneous deformational structures like convolute bedding and slump sheets have led to the interpretation of the psammo-pelitic sequence as turbidites characteristic of flysch. The deposition of turbidites was attributed to seismic phenomena. Although geochemical data are sparse, these rocks are richer in $Al_2O_3$ and poorer in $SiO_2$ than the average Archaean greywackes in general and greywackes of Dharwar craton in particular. Subaqueous sliding in a neritic to epineritic environment, or submarine shallow marine environment in a transgressive system, or tidal flat environment are the various depositional environments proposed based on different sediment structures and lithological variations. A minority view is that that these are deposited in a moderately deep ocean basin. In this model, the basal polymict conglomerate and associated wackes are interpreted as gravity or debris flows in a marine environment. Another model proposes that the conglomerates are proximal fan deposits, and pelites are the median or outer fan deposit in a fluvial system. Yet another model visualises polymict conglomerate as braided stream deposit, oligomict conglomerate as beach deposit and the wacke-arenite-shale facies as a fining upward megacycle in an intertidal flat. More detailed studies integrating the data from various sectors may lead to a better understanding of the overall depositional environment for these sediments.

Ortho-amphibolites associated with acid to basic tuffs represent syn-depositional magmatism within the Chaibasa Formation. An important component of this formation is the layered kyanite-tourmaline quartzite seen near Lapsa Buru. Compositional control together with fluid activity may be responsible for the formation of this interesting rock type.

Important rock units of Dhalbhum Formation are chlorite-sericite phyllites rich in magnetite and containing large porphyroblasts of andalusite and staurolite associated with chloritoid. Basic sills are interstratified with the phyllites. The lithological ensemble denotes an intertidal deposit having a provenance of low relief.

Three sets of folds and related fabrics of varying intensity, geometry and style are seen from different sectors of the Ghatsila domain.

### 4. Dalma Volcanics

Dalma lavas form a prominent belt of folded ultramafic-mafic volcanics and volcaniclastics associated with carbon phyllites overlying the Dhalbhum Formation. Details of the volcanics have been presented in the section on 'Volcanic Successions'.

### 5. Chandil Domain

The metasedimentary belt occurring between Dalma volcanics and Chhotanagpur Gneiss differs from the Ghatsila domain in the following features:

(i) metapelites are generally of low metamorphic grade,
(ii) there is an abundance of chert and carbonaceous shale-chert rhythmites and scarcity of siliciclastics,
(iii) there are large bodies of mafic-ultramafic rocks, as well as abundance of felsic volcanics,

(iv) impure limestones/dolomites are seen along the southern margin, to the north of Dalma volcanics,
(v) carbonatites are seen in the Tamar-Poropahar shear zone, and
(vi) syenite, nepheline syenite and S-type granite (Kuilapal and Chhendapathar) are seen.

An interesting feature of the Chandil Formation is the large volume of vitric, crystal and lithic tuffs present in the sequence, particularly near Chandil. They are essentially welded tuffs with lapilli, axiolites and crystal/lithic fragments, along with garnet phenocrysts and tourmaline needles. They range in composition from rhyolite to dacite and are similar to ash flow tuffs. Around Chandil, the rocks are least metamorphosed and as we proceed to the north, the rocks are metamorphosed in greenschist to transitional amphibolite facies. The psammapelites around Lawa show cross laminations and flaser to wavy to lenticular bedding, indicating alternation of current and wave action, that is typical of subtidal and inter-tidal zones.

Alkali syenites with nepheline and sodalite, and ultramafic-mafic intrusives, besides amygdular metabasalts, are common in the east. Acid volcanics and tuffs are also abundant. Large-scale $F_2$ folds around E-W axis with opposite sense of vergence in relation to the folds south of Dalma volcanics, are prominent. The contact of this succession with Chhotanagpur Gneiss is marked either by shearing or granitic veining in the TPSZ. Most workers have invoked N-S orthogonal compression across the belt to explain $D_1$ and $D_2$ deformations. $D_3$ folds are either regarded as cross folds or later phases of progressive folding deformation. Transtensile movements during the extensional regime, and transpressive movements during compressional regime in the orogen have been invoked. The sinistral pattern of $F_2$ folds is suggestive of anticlockwise rotation of the orogen against the stable Singhbhum granite in the south. Many workers have described two successive episodes of progressive metamorphism $M_1$ and $M_2$ coeval with two deformations $D_1$ and $D_2$. $M_3$ metamorphic phase is probably associated with retrogression related to $D_3$ deformation.

## GANGPUR AND KUNJAR GROUPS

A sigmoidal structural basin called the Gangpur basin (Fig.3S-7), originally described as an anticlinorium by M.S. Krishnan in 1937, was shown later by P.K. Banerji in 1968 as a reclined fold refolded into an antiform, which is modified by intrusion of granites. Gangpur Group consists of the following succession: carbonaceous metapelites intruded by basic sills, dolomites and limestones, a younger unit of carbonaceous metapelites, followed by mica

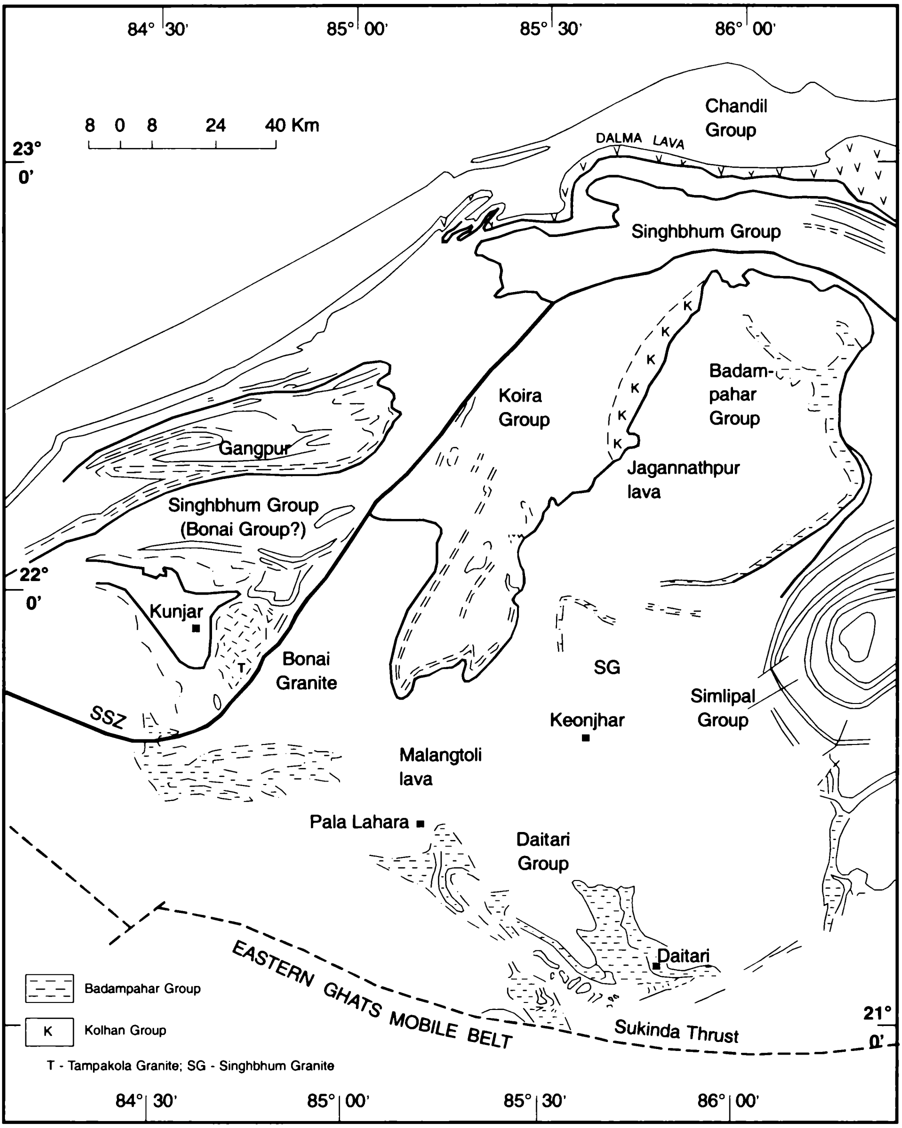

84° 30'
85° 00'
85° 30'
86° 00'
23° 0'
22° 0'
21° 0'
8 0 8 24 40 Km
Chandil Group
DALMA LAVA
Singhbhum Group
Koira Group
Badampahar Group
Jagannathpur lava
Gangpur
Singhbhum Group (Bonai Group?)
Kunjar
Bonai Granite
T
SSZ
SG
Keonjhar
Simlipal Group
Malangtoli lava
Pala Lahara
Daitari Group
Daitari
EASTERN GHATS MOBILE BELT
Sukinda Thrust
Badampahar Group
K Kolhan Group
T - Tampakola Granite; SG - Singhbhum Granite

**Fig.3S-7.** Geological outline map of western part of Singhbhum craton showing Gangpur and Kunjar basins (after Iyengar and Murthy, 1982). For details of stratigraphy, see Fig.3S-2 and the text. Structural trend lines are shown as dashed or thin lines.

schists and manganese silicate rocks known in older literature as gondites. Gangpur Group has been variously correlated in previous literature either with Koira Group or Singhbhum Group or the younger Kolhan Group. Similarly the Kunjar structural basin (Fig.3S-7), situated between Daitari Group at Deogarh in the south and Gangpur Group in the north, is correlated with Koira Group, Singhbhum Group or Kolhan Group. Detailed geological mapping of these regions is necessary before an acceptable correlation can be worked out.

## YOUNGER GRANITOIDS

Several granitoids intruding all formations except the Kolhan Group are scattered throughout the Singhbhum craton and North Singhbhum orogen. Some of them are composite bodies of Archaean basement and Proterozoic intrusion, while others are completely younger, of Proterozoic age. The important granitoids are Chakradharpur granite, Arkasani granite, Kuilapal granite and Mayurbhanj granite (Fig.3S-8).

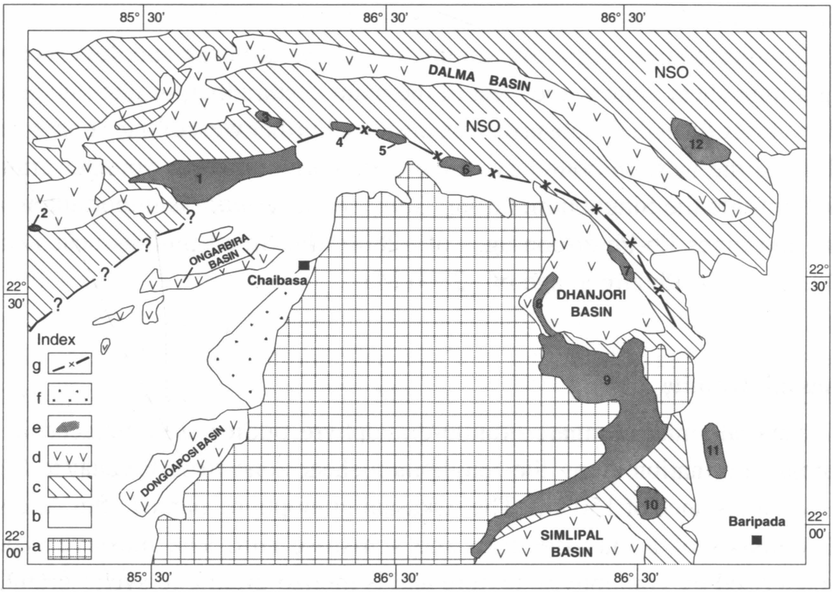


**Fig.3S-8.** Younger granites in Singhbhum and adjacent areas (after Mahadevan, 2002). 1 - Chakradharpur granite, 2 - Girga and Tebo granites, 3 to 7 -'Soda' granites and Arkasani granite; 8 to10 Mayurbhanj granite, 11 - Rompahari granite, 12 - Kuilapal granite, NSO - North Singhbhum orogen. *Index:* a - Singhbhum granite, b - Koira Group, c - Singhbhum Group, d - Volcanics, e - Younger granites, f - Kolhan Group, g - Singhbhum shear zone.

### Chakradharpur Granite

A sub-elliptical, E-W trending body of gneissic granite called the Chakradharpur Granite covering an area of 225 km$^2$ occurs along the southern margin of the North Singhbhum orogen. Koira Group occurs at the southern contact of the granite and Chaibasa Formation at the northern contact. Singhbhum shear zone passes through its northern boundary, although traditionally it is shown as a major fork along the southern boundary. The granite contains numerous enclaves of amphibolite, talc schist and arenaceous sediments that belong to the OMG and Koira Group. The gneissic granite shows three phases of deformation of which the first two ($F_1$ and $F_2$) are related to the deformation of supracrustals. The granite has two major components, viz., (i) the older grey trondhjemitic gneiss, which covers about three-fourths of the exposed area, and (ii) coarse-grained granodiorite to granite covering the remaining area. The older trondhjemitic gneiss is probably equivalent to Singhbhum granite (SG-A) and the younger granitoid intrusive into the Chaibasa Formation is of Proterozoic age. Geochemical modelling suggests that the older trondhjemites are produced by the partial melting of high-Mg amphibolites, whereas the late granitoids are formed by the partial melting of sialic crust, which includes the older trondhjemites.

Smaller bodies of granitic migmatites occur at Girga and Tebo near the Singhbhum shear zone to the west of the main Chakradharpur gneissic granite and probably form their subsurface extensions. Further west of the Bonai granite and along the western boundary of the craton are numerous younger granites which intrude the Singhbhum Group. *Tamperkola granite* is important among them and gives Pb-Pb zircon ages of ~2800 Ma. Small plutons near Daitari yield *in situ* Pb-Pb zircon age of ~2800 Ma.

### Arkasani Granite

Several small elongate granite-granophyre bodies are emplaced in the Chaibasa Formation along the Singhbhum shear zone from Porahat to Surda for over a distance of 150 km. The Arkasani granophyre, named after Arkasani hill, consists of a massive core and schistose rim. The massive type is characterised by granophyric texture and is monzo-granite to syeno-granite in composition. Microcline, albite and quartz are the essential constituents, whereas biotite, chlorite, muscovite, tourmaline, zoisite, apatite, sphene and opaque ore form the accessory minerals. The schistose granophyres are syn- to late kinematic in relation to $F_2$ deformation during which the intrusive dolerites are converted to hornblende schists in the Singhbhum shear zone.

The granophyres are marked by Sr depletion and enrichment in Ba. They show a slightly fractionated REE pattern with $Ce_N/Ce_Y$ ratios ranging from 1.52 to 9.49. The granophyres also show Eu anomaly and HREE enrichment. They are regarded as products of partial melting of crustal rocks. The granite has Rb-Sr age of 1000-1100 Ma.

### ‘Soda’ Granites and Felspathic Schists

Several small sheet like and lenticular bodies of granitoids ranging in composition from tonalite to granite are emplaced in the Singhbhum shear zone. Lit-par-lit injections of granitic material into metasediments are prominently seen, as in the case of Arkasani granite-granophyre. The name 'soda' granite is a misnomer because a wide spectrum of compositions is found and the granite is not necessarily sodic. Two prominent bodies of granite are studied, one south of Tatanagar and the other in the Mosabani-Kanyaluka area. The granites contain quartz, sodic plagioclase, microcline, muscovite, biotite and chlorite with accessory tourmaline, zircon, epidote, apatite, sphene and opaques. The granites are peraluminous, alkalic to alkali-calcic and are classified as granodiorite to adamellite. These granites become augen granites to felspathic schists with increasing deformation. The fine-grained groundmass of the felspathic schists amounts on the average to 90%. The granites are locally associated with layered / banded mylonites. In other areas, mylonites with mica 'fish' and 'bookshelf sliding' are noticed. Geochemical studies of 'soda' granites and Arkasani granophyre show that they are products of partial melting of a crustal source having a metasedimentary component. Fractionation of plagioclase probably played an important role in their petrogenesis.

Rb-Sr whole-rock ages of the 'soda' granite and granophyre range from 1100 to 1600 Ma with high $Sr_I$ ratios. $TD_M$ model ages and Sm-Nd ages of granites show that their precursor material could have a range of ages from 2300 to 2900 Ma. 'Soda' granite has a whole rock Pb-Pb age of ~2200 Ma. Younger events of 1600 and 1000 Ma are also recorded from some sectors. The overall picture is therefore that the ~1600 Ma event is a major one involving emplacement, deformation and metamorphism of these younger granitoids.

### Kuilapal Granite

Another elliptical body (12 x 6 km) of gneissic granite known as Kuilapal granite occurs at the eastern extremity of the North Singhbhum orogen, to the north of Dalma volcanics. The granite ranges in composition from trondhjemite to granite with a dominant granodiorite component. This body has also been emplaced synchronously with the deformation of surrounding mica schists, where higher grade of metamorphism producing staurolite, andalusite and sillimanite is noticed in the Chandil domain of the orogen. The granite hosts wolframite veins and is described as S-type crustal granite, like the other younger granites of the orogen. Kuilapal granite has given an Rb-Sr age of 1638±38 Ma and Pb-Pb ages of 2220 to 2000 Ma.

### Mayurbhanj Granite

A group of granitoids younger than the Dhanjori Group and Singhbhum Group occurring at the eastern margin of the Singhbhum craton is called Mayurbhanj granite by Saha (1994). Iyengar and Murthy (1982) called a part of the granite as Simlipal Granite. Many others have described these granites as granophyres. The main granitic body of irregular shape covers an area of about 1000 sq. km. Three other minor bodies occur at Notopahar, Nilgiri and Chakdar Pahar. The Romapahari granite is a small tongue of the main granite body (Fig.3S-5). The main granite body is divisible into three units viz:

1. Fine grained hornblende-biotite (±stilpnomelane±riebeckite) granophyric granite
2. Coarse grained ferrohastingsite-biotite (±hedenbergite) granite intrusive into the granophyric granite
3. Biotite aplogranite intrusive into ferrohastingsite-biotite granite

All the three types are rich in magnetite. The granophyric granite is alkali felspar granite and the ferrohastingsite granite is normal granite. There is a controversy whether the granophyric granites are gradational to the Mayurbhanj gabbro-anorthosite suite near Gorumahisani or whether they are independent of each other. Mayurbhanj granite intrudes Singhbhum granite and Kaptipada granite as well as the gabbro-anorthosite bodies.

Mayurbhanj granite is characterised by high $SiO_2$, alkalis and Fe/Mg, and low CaO, MgO and Sr. Chondrite normalised REE pattern shows strongly negative Eu anomaly, flat HREE and low degree of fractionation ($Ce_N/Yb_N$=4.95). These are typical of A-type granites, derived by the partial melting of the crust, as is also evidenced by high initial Sr isotope ratios.

The Mayurbhanj granite in Simlipal gives an Rb-Sr age of 2084±70 Ma with $Sr_I$ of 0.72526. The recent *in situ* Pb-Pb zircon dating of Mayurbhanj granite has given ages of 3080±8 Ma and 3092±5 Ma, corresponding to the age of Singhbhum granite (SG-B). The Pb-Pb age is interpreted as the age of emplacement since the zircons are believed to be non-xenocrytic (Misra, 2006). Rb-Sr age probably denotes a younger thermal event in the area that has affected the granite. These anomalous ages are to be resolved by further dating.

## KOLHAN GROUP

### Kolhan Basin

The type area of Kolhan Group is the Kolhan basin trending NNE-SSW for 60 km, with an average width of 10-12 km, from Chaibasa to Noamundi. Kolhan basin unconformably overlies the Singhbhum granite, Jagannathpur (Dungoaposi) lava and Koira Group. Parts of the boundaries with Jagannathpur lavas and Koira Group are faulted. Kolhan Group is divided into three formations as given below (Singh, 1998):

| | |
|---|---|
| Kolhan Group | Jetia Shale<br>Jhinkpari Limestone<br>Mungra Sandstone |

The basal formation is about 25m thick and comprises conglomerates and sandstones. The conglomerate contains pebbles of BIF from Koira Group and granite from the basement. The middle Jhinkpari Limestone is 20 m thick and consists of a lower limestone and an upper shale. The limestone unit has a lower grey and an upper purple limestone grading to siliceous limestone laterally. The limestone locally shows columnar stromatolites. In Chaibasa area, the limestone contains manganese nodules. Jetia Shale about 200 m thick has three facies viz., purple shale, calcareous shale and limestone. The source of sediments in Kolhan Group is from the east and southeast.

The basin consists of three structural belts viz., eastern belt of dome and basin structures, a western homocline passing into a thrust and a zone of inverted isoclinal folds marked by structural terraces. The deformation pattern may be attributed to limited areal extent and thickness, and faulting in the west. The age of the basin is not well constrained, but may be around 1600 Ma. Singhbhum craton does not contain any known 'Purana basins', but the Kolhan basins may be their equivalent.

### Nomira Basin

Kolhan Group in the Nomira basin consists of a low west-dipping (5 to 15°) sequence of grey quartz arenite (locally arkosic) with several thin bands of grey shales. A few bands of pyrophyllite are also noticed locally. Nomira basin is faulted against the Malangtoli (Nuakot) volcanics and Koira Group, and overlies Singhbhum granite unconformably. The sediment source for the basin is from the east. Some workers correlate this basin with Koira Group.

### Mankarchua Basin

This basin covers an area of 100 sq. km north of Pala Lahara where dissected outcrops of south-dipping orthoquartzites (locally pebbly) have a faulted contact with Pala Lahara gneiss. The orthoquartzites, about 50 m thick, overlie Malangtoli (Nuakot) lavas. The provenance for this basin appears to be Pala Lahara gneiss.

**Kamakhyanagar Quartzite** has been correlated with Kolhan Group and consists of alternations of cross bedded and cherty quartzites bounded by faults on either side. In the north it is faulted against the Daitari Group. The correlation of this band with Kolhan Group is debatable.

## NEWER DOLERITE

A prominent basic dyke swarm called the Newer Dolerite trending in a dominant NNE to NE and a subordinate NW direction traverses the entire craton. The dykes range in width from 10 cm to one km and length from a few meters to over 20 km, and have on the average a spacing of one to four km. The dykes are predominantly quartz dolerites, belonging to two groups called ND I and ND II. Other types of dykes are peridotites, norites and lamprophyres as well as microgranites and leucogranophyres, within and at the margin of dolerites. A large norite dyke near Durgapur consists of orthopyroxene, plagioclase and subordinate diopsidic augite. The lamprophyric dyke near Maluka consists of euhedral diopside and barkevitite-hastingsite.

Quartz dolerites consist of plagioclase and clinopyroxene, which are altered respectively to saussurite and uralite. Ilmenite, sphene and stilpnomelene are accessories. Granitic wall rocks are transformed to leucogranophyre and xenolithic granophyre due to partial melting.

Group I dolerites are Fe-tholeiites and Group II range from Mg-Fe tholeiites to komatiitic basalts. The entire suite is characterised by high K/Rb ratios, high Ni, Co and low Rb, Ba and Sr. Geochemical modelling indicates picritic source for Newer Dolerite. Rb-Sr age of ultramafic dyke is ~2600 Ma. K-Ar dates of dolerites show a grouping into three ages 2000±100 Ma, 1500±100 Ma and 1100±100 Ma. Palaeomagnetic studies of Newer Dolerite also indicate three episodes of igneous activity.

*Ultramafic intrusions* occur in 80 km long belt at the western boundary of Singhbhum granite from Rajnagar to Champua, and in the northeast near Manpur. They are mainly peridotites grading from poikilitic harzburgites to pyroxene-rich harzburgite.

## TECTONIC EVOLUTION

Tectonic models of evolution of Singhbhum craton, North Singhbhum orogen and Chhotanagpur Gneiss (part of Satpura mobile belt) are summarised by Gupta and Basu (2000) and Mahadevan (2002).

### Early Crust

The earliest crust represented in Singhbhum craton is the Older Metamorphic Group, which has an age indistinguishable from the Old Metamorphic

Tonalite Gneiss that intrudes it. Although isotopic evolutionary models may indicate the presence of older events (e.g. ~3600 Ma), the first identifiable crustal accretionary event is 3300-3400 Ma. Pelitic rocks, with accessory zircon of continental derivation in the OMG, suggest that sialic crust was in existence prior to the formation of OMG. Models of tectonic evolution involving early ultramafic-mafic crust that was recycled into the mantle through mantle convection and generation of TTG gneisses by two stage melting have been proposed for the evolution of early continental crust by various authors. This view has been adopted by some workers for the evolution of early crust in Singhbhum craton.

The oldest component of Singhbhum granite (SBG-A) is also 3300-3400 Ma in age, although it encloses xenoliths of OMTG and is therefore younger. The greenstone belt of Badampahar Group is probably intruded by the younger phase of Singhbhum granite (SBG-B). Badampahar Group is regarded as either younger than or homotaxial with OMG, although their gross lithological association is different. Probably they form a unified association of ensialic (OMG) to ensimatic lithologies (Badampahar), dismembered into screens and enclaves by later deformation and granitic magmatism. Badampahar Group is characterised by the presence of spinifex textured komatiites, pillowed tholeiites, banded iron formations and fuchsite quartzite that are common in Archaean greenstone belts. From the state of preservation of greenstone belts as narrow scattered linear bodies swamped by a large volume of younger granites, it is difficult to be certain about the tectonic environment, although models suggesting ocean opening by continental rifting and ocean closing by compression are popular for this ensemble.

The next cycle is marked by the Dhanjori (Simlipal) Group of ~2800 Ma that is marked by basal QPC and basalt-quartzite cycles and basic intrusions, similar to Neoarchaean-Palaeoproterozoic successions of the world. This is followed by the Koira Group or the main Iron Ore Group of Sarkar and Saha (1983). Koira Group is characterised by the presence of basal QPC resting non-conformably on Singhbhum granite. A succession of carbonaceous phyllites, limestones, manganese formations, metabasic volcanics and banded iron formation characterises this group. Presence of stromatolites and cynobacteria suggest that primitive forms of life were first preserved in this group. Koira iron ore basin may be compared to a marginal basin sited on a continental crust that was involved in a major event of plume activity. The continental crust of Singhbhum craton was probably stabilised during this major crustal accretion event. This event is followed by the evolution of North Singhbhum orogen consisting of a thick sequence of Singhbhum Group.

## North Singhbhum Orogen

The evolution of North Singhbhum orogen has been visualised in terms of several models of crustal evolution. The success of the models will largely depend on their strength to conform to plate tectonic models as applicable to the Precambrian. A N-S cross-section of the craton up to Chhotanagpur Gneiss is given here (Fig.3S-9) for a clearer understanding of various tectonic models. The various models proposed are discussed below:

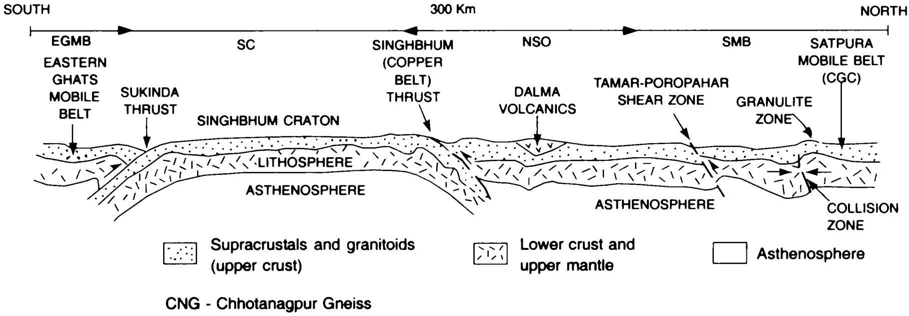

SOUTH
300 Km
NORTH
EGMB
EASTERN GHATS MOBILE BELT
SC
SUKINDA THRUST
SINGHBHUM CRATON
SINGHBHUM (COPPER BELT) THRUST
NSO
DALMA VOLCANICS
TAMAR-POROPAHAR SHEAR ZONE
SMB
GRANULITE ZONE
SATPURA MOBILE BELT (CGC)
LITHOSPHERE
ASTHENOSPHERE
ASTHENOSPHERE
COLLISION ZONE
Supracrustals and granitoids (upper crust)
Lower crust and upper mantle
Asthenosphere
CNG - Chhotanagpur Gneiss

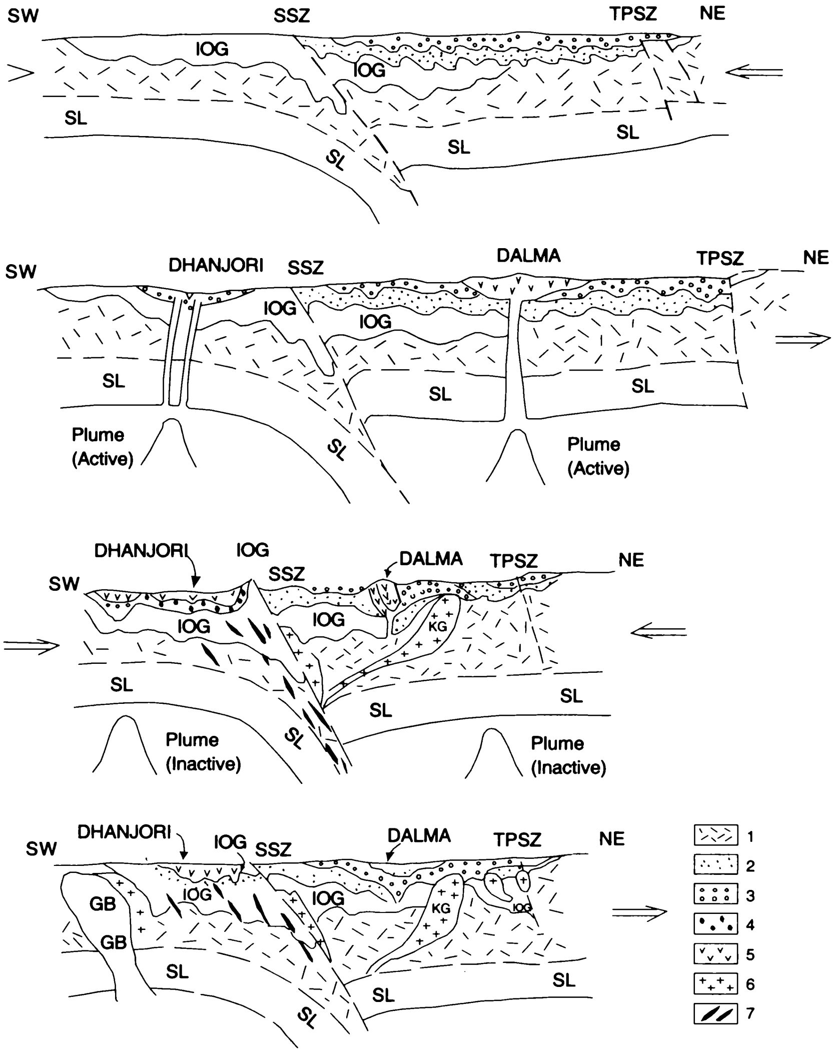
**Fig.3S-9.** Diagrammatic N-S cross-section across Singhbhum craton (after Saha, 1994, p.317).

### Intraplate Subduction

S.N Sarkar and A.K. Saha (1983) (Fig.3S-10) visualise the Singhbhum shear zone as the suture between the Singhbhum craton and Chhotanagpur Gneiss (CGC). The stages in the evolution of the suture zone are described below.

(i) Formation of ocean around the craton at 2.2 Ga in which sediments of North Singhbhum orogen are deposited.
(ii) Northward subduction of the craton below CGC and folding and metamorphism of Singhbhum Group.
(iii) Tensional phase of Dhanjori-Dalma volcanism and emplacement of gabbro-anorthosite.
(iv) Renewed subduction and partial melting of the cratonic plate to produce granites and granophyres (Arkasani, Chakradharpur, Mayurbhanj, Kuilapal etc.).
(v) Renewed compression, folding and transcurrent / thrust faulting along the Singhbhum shear zone, forming the suture.

The difficulties with the model are the absence of petrotectonic assemblages in the suture (which is a common drawback in most Precambrian models), lack of evidence for large-scale transport across the Singhbhum shear


SW
SSZ
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DALMA
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NE
IOG
IOG
SL
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Plume (Active)
Plume (Active)
DHANJORI
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Plume (Inactive)
Plume (Inactive)
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**Fig.3S-10.** Intraplate subduction model of Sarkar and Saha (1983). 1 - Continental lithosphere, 2 - Chaibasa Formation, 3 - Dhalbhum Formation, 4 - Dhanjori conglomerate, 5 - Dhanjori, Dalma lavas, 6 - Singhbhum granite, 7 - Ultramafites. SL - Subcrustal lithosphere, IOG - Iron Ore group, GB - Gabbro, KG - Kuilapal granite, SSZ - Singhbhum shear zone, TPSZ - Tamar-Poropahar shear zone.

zone and the problem of a major intervening tensile phase associated with extensive oceanic volcanism in an overall compressive regime.

## Ensialic Orogeny

The essential features of this model (Fig.S3-11) by A. Gupta and A. Basu (2000) are the rift-related volcanism on the craton (Dalma, Dhanjori) with concurrent development of sedimentary basins. The compressional regime that

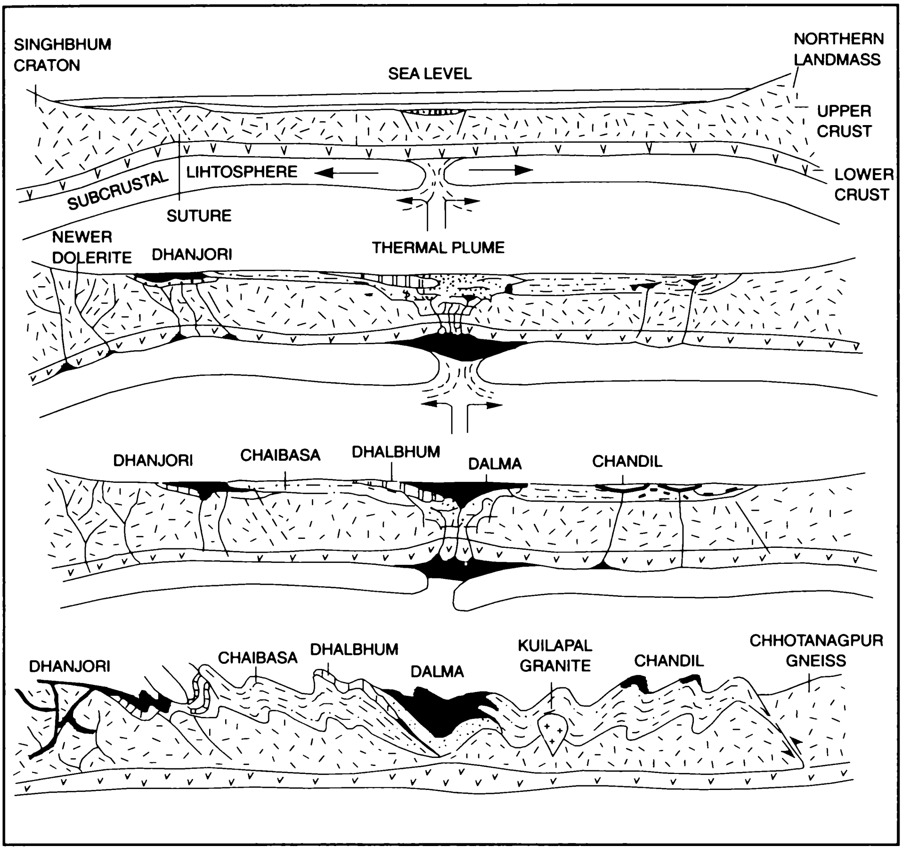

SINGHBHUM CRATON
NORTHERN LANDMASS
SEA LEVEL
UPPER CRUST
LOWER CRUST
LIHTOSPHERE
SUBCRUSTAL
SUTURE
NEWER DOLERITE
DHANJORI
THERMAL PLUME
DHANJORI
CHAIBASA
DHALBHUM
DALMA
CHANDIL
DHANJORI
CHAIBASA
DHALBHUM
DALMA
KUILAPAL GRANITE
CHANDIL
CHHOTANAGPUR GNEISS

**Fig.3S-11.** Model of rifting and ensialic orogeny of Gupta and Basu (2000).

followed was triggered by delamination and sinking of subcrustal lithosphere leading to ensialic orogeny. This model gains limited support from the geochemistry of basic lavas, which may be related either to back-arc or continental rift settings. The model visualises a single continuous landmass of Singhbhum craton together with Chhotanagpur Gneiss (CGC) for which there is no geochronological evidence of older Archaean ages in CGC.

### Plate and Plume Tectonic Model

P.K. Banerji and S.K. Ghosh (1994) propose two events of plume activity, the first one forming a series of lavas (Simlipal, Ongarbira) involved in seafloor spreading followed by orogeny and the second one forming another series of lavas (Dhanjori) after cratonisation. The difficulty with the model is the long-lived plume in the area despite one earlier orogeny, lack of lavas of intermediate composition like andesites, and presence of conspicuous arenite interbeds in the lavas of Simlipal basin.

## Collision of Microplates

A.N. Sarkar (1988) proposed three cycles of microplate collision (Fig.3S-12) between Singhbhum craton and Chhotanagpur Gneiss. The first cycle saw the evolution of Dalma lavas as ophiolites, the second cycle resulted in the development of rotation of plates, intense folding and transcurrent shear zones. The third cycle resulted in the obduction of the continental lithosphere. The collision of microplates spans a period of about 300 m.y. requiring too slow motion of plates in Precambrian. This model also does not account for differences in age of Singhbhum craton and Chhotanagpur Gneiss.

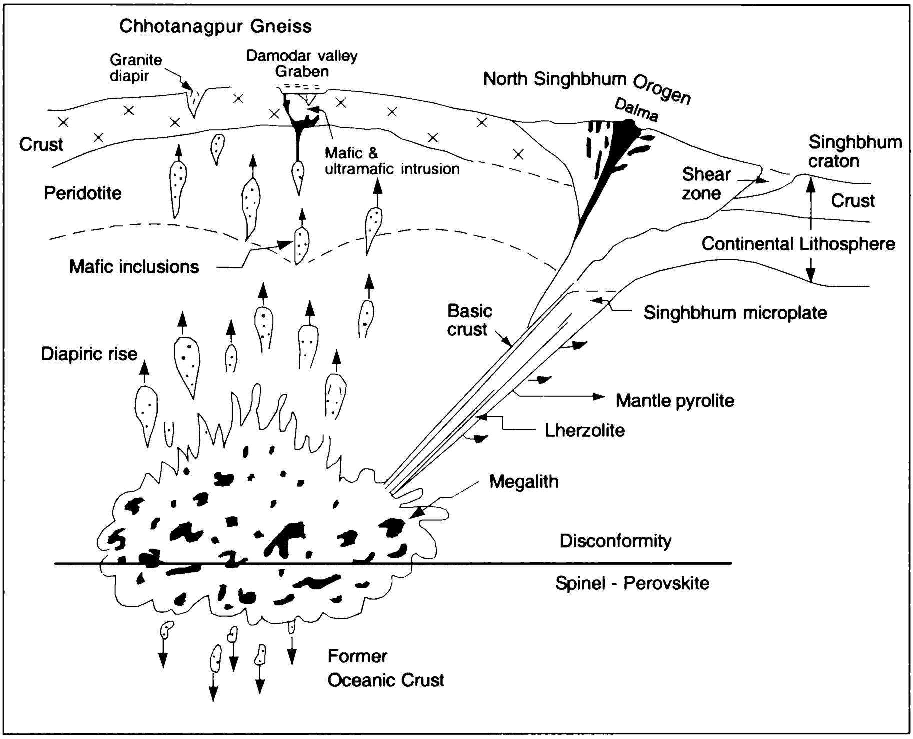

Chhotanagpur Gneiss
Granite diapir
Damodar valley Graben
North Singhbhum Orogen
Dalma
Crust
Mafic & ultramafic intrusion
Singhbhum craton
Peridotite
Shear zone
Crust
Continental Lithosphere
Mafic inclusions
Singhbhum microplate
Basic crust
Diapiric rise
Mantle pyrolite
Lherzolite
Megalith
Disconformity
Spinel - Perovskite
Former Oceanic Crust

**Fig.3S-12.** Collision model of Sarkar (1988).

## Back-arc Marginal Basin Model

M.K.Bose (1994) proposed (Fig.3S-13) that North Singhbhum orogen was a back-arc marginal basin accreting to the Singhbhum craton. A mid-basin rift was formed at the site of Dalma volcanism. Chhotanagpur Gneiss represented the root zone of island arc. The complex evolution of CGC described in the section on Satpura mobile belt negates the simplistic island arc-back arc model for CGC.

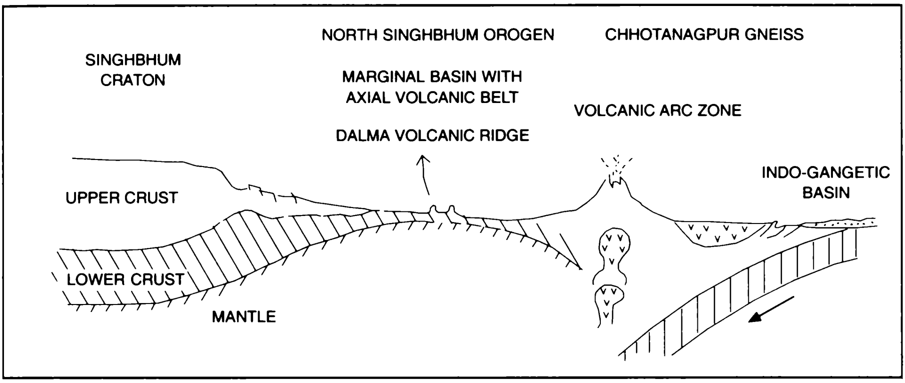

NORTH SINGHBHUM OROGEN
CHHOTANAGPUR GNEISS
SINGHBHUM CRATON
MARGINAL BASIN WITH AXIAL VOLCANIC BELT
VOLCANIC ARC ZONE
DALMA VOLCANIC RIDGE
INDO-GANGETIC BASIN
UPPER CRUST
LOWER CRUST
MANTLE

**Fig.3S-13.** Back-arc marginal basin model (modified after Bose, 1994).

## Mantle Interaction Model

T.M. Mahadevan (2002) proposed a model of evolution for cratonic greenstone belts (Singhbhum craton) and the adjoining high-grade terrains (granulite belt in CGC close to North Singhbhum orogen), separated by numerous shear zones. Greenstone belts were stationed above downgoing zones in the convecting mantle, and correspondingly, high-grade terrains were sited over upwelling mantle, in this model of interaction between the continental crust and hot mantle. Differential exhumation along shear zones has exposed the two distinct types of terrains. Shear zones are not considered as collisional suture zones because of lack of typical petrotectonic assemblages.

## Conclusion

The plethora of models proposed for the evolution of Singhbhum craton and Chhotanagpur Gneiss exposes the inadequacy of our database and the fluid state of our knowledge on Precambrian tectonic environments. With advancing frontiers of our geological knowledge and accumulation of new information in different fields, we may hopefully understand better the tectonic evolution of the craton, the marginal orogen and the adjoining mobile belts.

# BUNDELKHAND CRATON

## INTRODUCTION

Bundelkhand craton named for the fifteenth century Kingdom of Bundelkhand is a triangular region having semi-circular sides, and covers an area of 26,000 km$^2$ (Fig.3BK-1). If the concealed part of the craton in the north beneath the Indo-Gangetic Alluvium is considered, the total area may go up to 35,000 km$^2$. Bundelkhand craton is separated from the Satpura mobile belt (CITZ) in the south and the Aravalli craton in the west by the Proterozoic Vindhyan basin. Vindhyan basin is in contact with CITZ along the Son-Narmada North Fault (SNNF) and is juxtaposed against Aravalli craton along the Great Boundary Fault (GBF). The Aravalli and Bastar cratons, as well as Chhotanagpur Gneiss forming part of Satpura mobile belt, are the other major shield elements that occur in the immediate neighbourhood of Bundelkhand craton (Fig.3BK-2). The southern margin of the craton shows a steep gravity gradient, which is a reflection of the nearby SONA (Son-Narmada) Faults. The northern contact towards the alluvium is marked by a low gravity gradient. Aeromagnetic

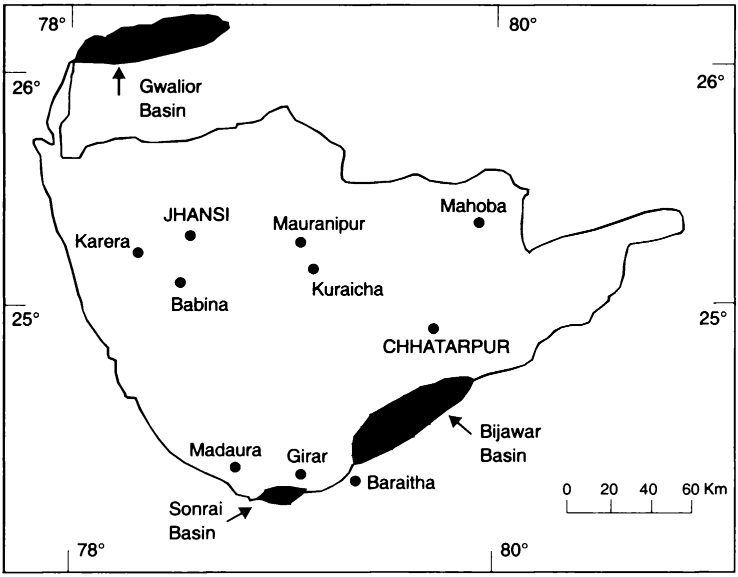

78°
80°
26°
26°
Gwalior
Basin
JHANSI
Mauranipur
Mahoba
Karera
Babina
Kuraicha
25°
25°
CHHATARPUR
Bijawar
Basin
Madaura
Girar
Baraitha
Sonrai
Basin
0 20 40 60 Km
78°
80°

**Fig.3BK-1.** Simplified geological map of Bundelkhand craton (after Sharma and Rahman, 2000).

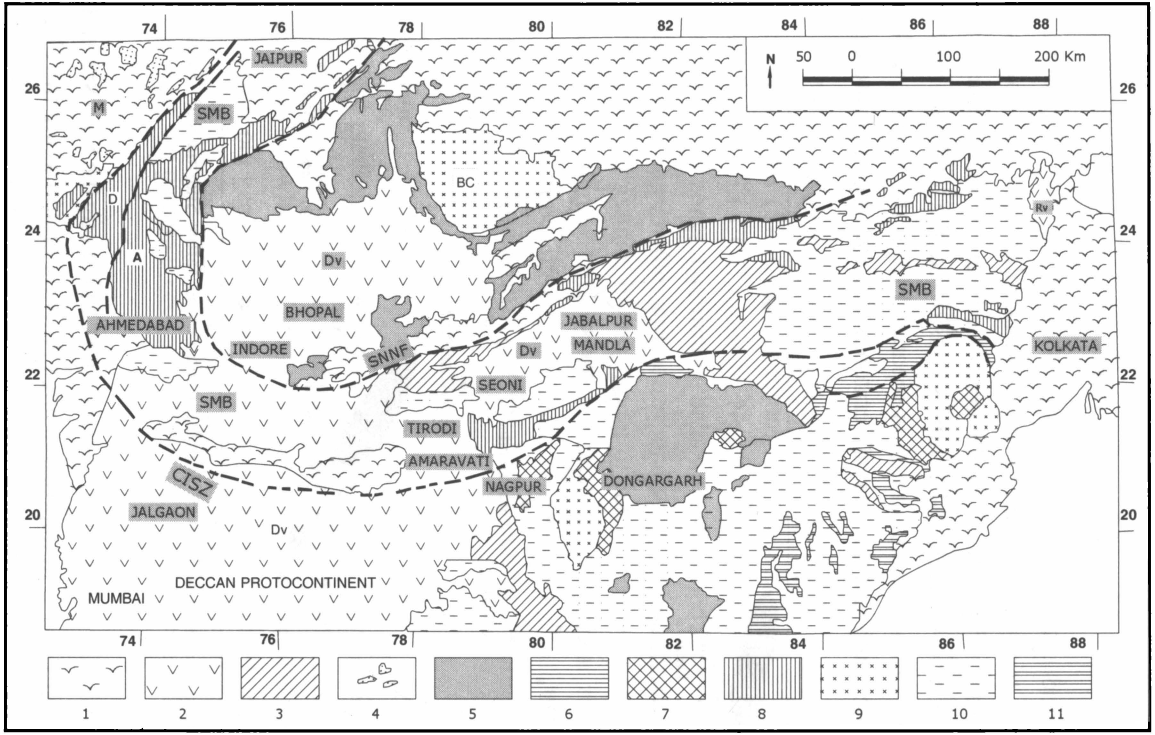

74
76
78
80
82
84
86
88
26
24
22
20
N
50 0 100 200 Km
JAIPUR
SMB
M
D
A
BC
Rv
Dv
BHOPAL
AHMEDABAD
INDORE
SNNF
JABALPUR
MANDLA
Dv
SMB
KOLKATA
SEONI
SMB
TIRODI
AMARAVATI
NAGPUR
DONGARGARH
CISZ
JALGAON
Dv
DECCAN PROTOCONTINENT
MUMBAI
1
2
3
4
5
6
7
8
9
10
11

**Fig.3BK-2.** Bundelkhand craton (BC) surrounded by Satpura mobile belt (SMB) and adjoining cratons. 1 - Alluvium, 2 - Deccan (Dv) and Rajmahal (Rv) volcanics, 3 - Gondwana basins, 4 - Malani Igneous Suite in Marwar craton (M), 5 - Purana basins, 6 - Singhbhum and Chilpi Groups, 7 -Sakoli, Nandgaon, Sonakhan, Koira, Daitari and Simlipal sequence, 8 - Aravalli (A), Delhi (D), Mahakoshal, Sausar, Sarguja, Kodarma and Ranchi squences, 9 - Bundelkhand, Dongargarh and Singhbhum granites, 10 - Unclassified gneisses, 11- Eastern Ghats Mobile Belt. CISZ - Central Indian Shear Zone. SNNF - Son Narmada North Fault (after Yedekar et al. 1990).

surveys indicate the extension of the Bundelkhand granite beneath the Proterozoic cover sediments.

### Previous Work

Early geological studies by H.B. Medlicott, A.R.Mallet and C.A. Hacket in the nineteenth century were followed by sporadic later work summarised by Jhingran (1958) and Basu (1986). Stratigraphic studies by M.N. Saxena, R.Prakash and co-workers, R.C. Mishra and R.P. Sharma were reviewed by K.K. Sharma (Sharma and Rahman, 2000). Geochemical and geochronological studies by S.M. Zainuddin, M.E.A. Mondal and co-workers and regional review by Soni and Jain (2001) are summarised in GSI (2004a).

### Main Components

The Archaean Bundelkhand granite with supracrustal enclaves covers the entire craton (Fig.3BK-3). Numerous prominent quartz reefs that host pyrophyllite-diaspore deposits and sub-economic basemetal mineralisation traverse the granite. Palaeoproterozoic basins of small extent occur to the south (Bijawar and Sonrai) and to the north (Gwalior), and the great Vindhyan basin surrounds the craton. These 'Purana' basins are described in Chapter 5 on Proterozoic Sedimentary Basins.

The main components of the craton are the following:

1. Enclave suite of supracrustal rocks within orthogneisses.
2. Bundelkhand granite with associated quartz reefs and rare felsic volcanics.
3. Mafic dyke swarms.

## SUPRACRUSTALS AND GNEISSES

### Supracrustals

Two prominent east-west trending belts of enclaves are noticed viz., (i) northern belt extending from Karera to Kabrai, through Babina, Kuraicha, Jhansi, Mauranipur and Mahoba, and (ii) southern belt from Madaura to Baraitha through Girar (Fig.3BK-1). Other linear enclaves are noticed near Panna and Kalinjer. These belts have a regional trend of E-W with northerly dips. The enclaves consist essentially of BIF with amphibolites, ultramafics and minor quartzite, metapelite and marble. The enclave suite was earlier classified into groups and formations under various names such as Mehroni, Rajaula, Kuraicha, Palar, Berwar, Madaura and Mauranipur. Such stratigraphic distinctions made

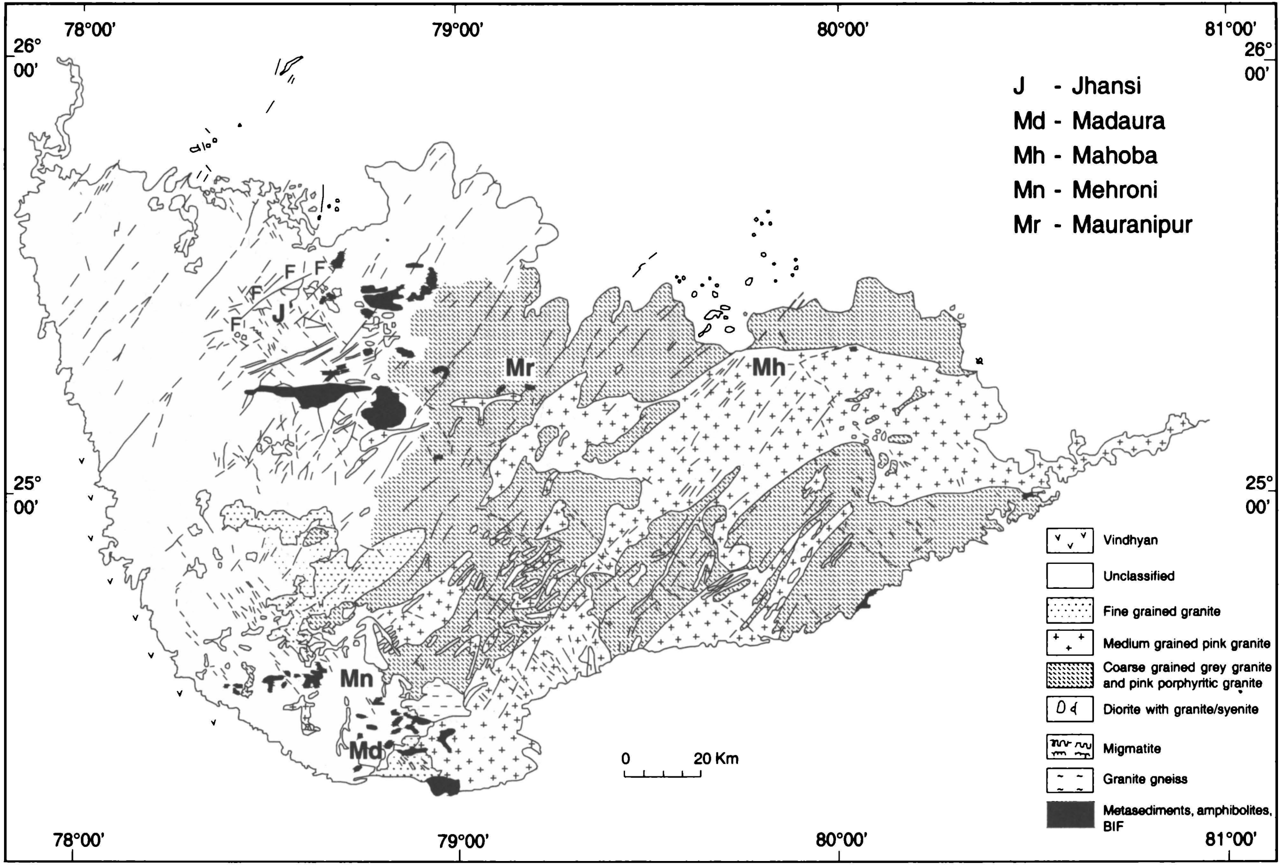

78°00'
79°00'
80°00'
81°00'
26° 00'
25° 00'
J - Jhansi
Md - Madaura
Mh - Mahoba
Mn - Mehroni
Mr - Mauranipur
F
J
Mr
Mh
Mn
Md
0
20 Km
Vindhyan
Unclassified
Fine grained granite
Medium grained pink granite
Coarse grained grey granite and pink porphyritic granite
Diorite with granite/syenite
Migmatite
Granite gneiss
Metasediments, amphibolites, BIF

**Fig.3BK-3.** Geological map of Bundelkhand craton (after Soni and Jain, 2001; GSI, 2004).

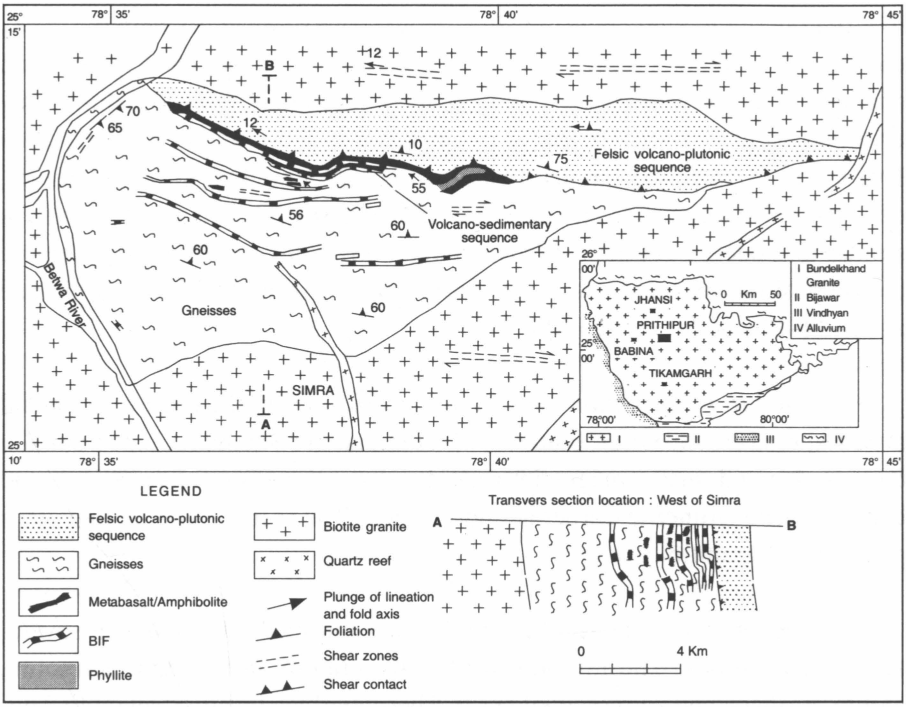

25° 15'
78° 35'
78° 40'
78° 45'
25° 10'
12
70
65
10
55
75
56
60
60
60
B
A
SIMRA
Felsic volcano-plutonic sequence
Volcano-sedimentary sequence
Gneisses
Betwa River
26° 00'
25° 00'
JHANSI
PRITHIPUR
BABINA
TIKAMGARH
0 Km 50
I Bundelkhand Granite
II Bijawar
III Vindhyan
IV Alluvium
78° 00'
80° 00'
I
II
III
IV
LEGEND
Felsic volcano-plutonic sequence
Gneisses
Metabasalt/Amphibolite
BIF
Phyllite
Biotite granite
Quartz reef
Plunge of lineation and fold axis
Foliation
Shear zones
Shear contact
Transvers section location : West of Simra
A
B
0
4 Km

**Fig.3BK-4.** Geological map of enclave suite near Prithipur (after Hanuma Prasad et al. 1999).

only on the basis of differences in degree of metamorphism and on lithological ensemble in different areas are not tenable on a regional scale, and therefore the lithologies will be described here without assigning them stratigraphic names. One such enclave suite is illustrated in Fig.3BK-4.

*Ultramafic rocks* are mainly peridotites, dunites, pyroxenites and gabbros closely associated with metabasic rocks and BIF. They form melanosomes of migmatites and occur as discrete patches in granites as near Jhansi and Karera. They are widespread in the gneisses of southern belt near Madaura and Baraitha. Peridotite enclaves contain 30-38% MgO, 10-13% $Fe_2O_3$(t), 43-47% $SiO_2$, high Cr and Ni. The associated gabbros are also rich in Mg and Cr. Similar ultramafic rocks are seen near Kuraicha and Kabrai in the northern belt. Some of them show veinlets of chrysotile asbestos. Talc-tremolite schists and tremolite-actinolite schists are also common. Unconfirmed reports of diamondiferous ultramafic rocks (kimberlites or lamproites?) are recorded in literature.

*Metabasic rocks* are the most abundant among the enclaves in the southern and northern belts. They range in composition from schistose metabasalts to low-grade amphibolites some of which show primary volcanic structures. They contain tremolite-actinolite, bluegreen hornblende, plagioclase, sphene and opaques. Some of them contain clinopyroxene and anthophyllite. Basaltic pillow lava and basaltic komatiite occur as enclaves near Mauranipur. The pillow lava is low K tholeiitic basalt to basaltic andesite enriched in LIL elements, depleted in HFS elements and have flat REE patterns. The basaltic komatiite is similar to modern boninite (Malviya et al. 2006). Some enclaves are gabbroic in composition and texture. A metabasic enclave from Mahoba has yielded zircon Pb-Pb age of 3249±5 Ma.

*Banded Iron Formation* is the most conspicuous in the enclave suite and is widespread around Girar, Baraitha, Mauranipur and Babina. Compositionally they are banded quartz-magnetite rock, banded magnetite-grunerite rock and banded quartz-grunerite-garnet-actinolite rock. These form low mounds in a peneplained granitic country.

*Carbonate rocks* are seen as small lenses intruded by granites in several scattered localities. The marbles are locally impure and contain actinolite, biotite, felspars, and some scapolite (?). These marbles locally grade into calc-silicate rocks. Some of these are suspected to be carbonatites.

*Quartzites* also occur as scattered lenses and bands. Some of them contain biotite and garnet. Some are indistinguishable from sheared quartz reefs.

*Metapelites* are rather rare, and when present consist of garnet, biotite and sillimanite. Some biotite-garnet-hornblende schists seen near Mauranipur are described as greywackes. While some authors regard the rocks of Mauranipur basin as a younger sequence deposited on Bundelkhand granite, or as equivalents of Proterozoic Sonrai/Bijawar basins, others classify them with the enclave suite.

The enclave suite also records three phases of folding similar to the associated banded gneisses, and together constitutes ancient supracrustals with the TTG gneisses forming the earliest event in the craton at 3200-3300 Ma.

### Gneisses

Grey and pink banded (stromatic) to streaky (schlieric) gneisses occur as slivers, rafts and narrow belts within vast areas of younger Bundelkhand granite. In the stromatic gneisses, biotite and hornblende bearing granodiorite melanosomes occur as bands or rafts in leucosomes. Schistose amphibolite also occurs as melanosomes that are disrupted to mafic schlieren in streaky gneisses. Polyphase banded gneisses show early tight to isoclinal and reclined folds ($F_1$), which are refolded by reclined folds ($F_2$) that are coaxial and coplanar with $F_1$ folds. The third set of folds is open to close, disharmonic folds. Superposed fold patterns including hook shapes are common. Subsequent to folding the gneisses have undergone two phases of shearing.

The gneisses are best exposed in the Sprar river section near Kuraicha, at Rampura and south of Babina. They have highly fractionated REE patterns with HREE and Yb depletion and no significant Eu anomaly, and thus resemble Archaean TTG suites. They may have been produced by partial melting of basaltic crust in a high geothermal regime, with retention of garnet and hornblende as residual phases. The gneisses near Mahoba and Kuraicha are a high-Al trondhjemites containing quartz, plagioclase, magnetite, apatite and zircon. They are dated by ion microprobe and provide zircon Pb-Pb age of 3270 and 3300 Ma respectively. It is significant that a basic enclave in the gneiss at Mahoba also gave an age of 3250 Ma. Another outcrop of gneiss was noted at Lota Pahar near Kabrai, which is a typical high-Al trondjhemite that gives Sm-Nd model age of 3200 Ma. The gneiss at Babina gave ages of 2700 to 2900 Ma. The gneisses at Karera and Panchwara are low Al-trondhjemites, which have moderately fractionated REE pattern, small negative Eu anomaly and Yb depletion. They yield ages of 2500-2550 Ma that correspond to the age of younger Bundelkhand granite. These dates suggest an earlier orogenic episode at 3200-3300 Ma.

## BUNDELKHAND GRANITE

The vast country of Bundelkhand granite represents a large plutonic complex of batholithic dimension. In an earlier attempt at classification of this complex based on mutual field relations and petrography, three types of granite were recognised (Basu, 1986), namely, (i) coarse grained porphyritic granite, (ii) medium grained porphyritic granite, and (iii) leucogranite, each with numerous sub-types. Recent geochemical studies have helped to identify four phases of granite viz., (i) hornblende granodiorite, (ii) porphyritic biotite granite, (iii) coarse porphyritic granite, and (iv) leucogranite. Hornblende granite is metaluminous, calc alkaline and has moderately fractionated REE, low Yb and insignificant Eu anomaly like the Archaean TTG suites, and is produced by hydrous partial melting of hornblende/garnet bearing mafic source. Porphyritic biotite granite that intrudes the hornblende granite is Y-undepleted, moderately fractionated, I-type calc alkaline monzogranite with negative Eu anomaly, and is generated by the melting of felsic crust. Later intrusions of coarse porphyritic granite and leucogranite are peraluminous monzo- and syeno-granites. These granites are moderately fractionated and enriched in Yb, Y, Zr, Th, K and Rb

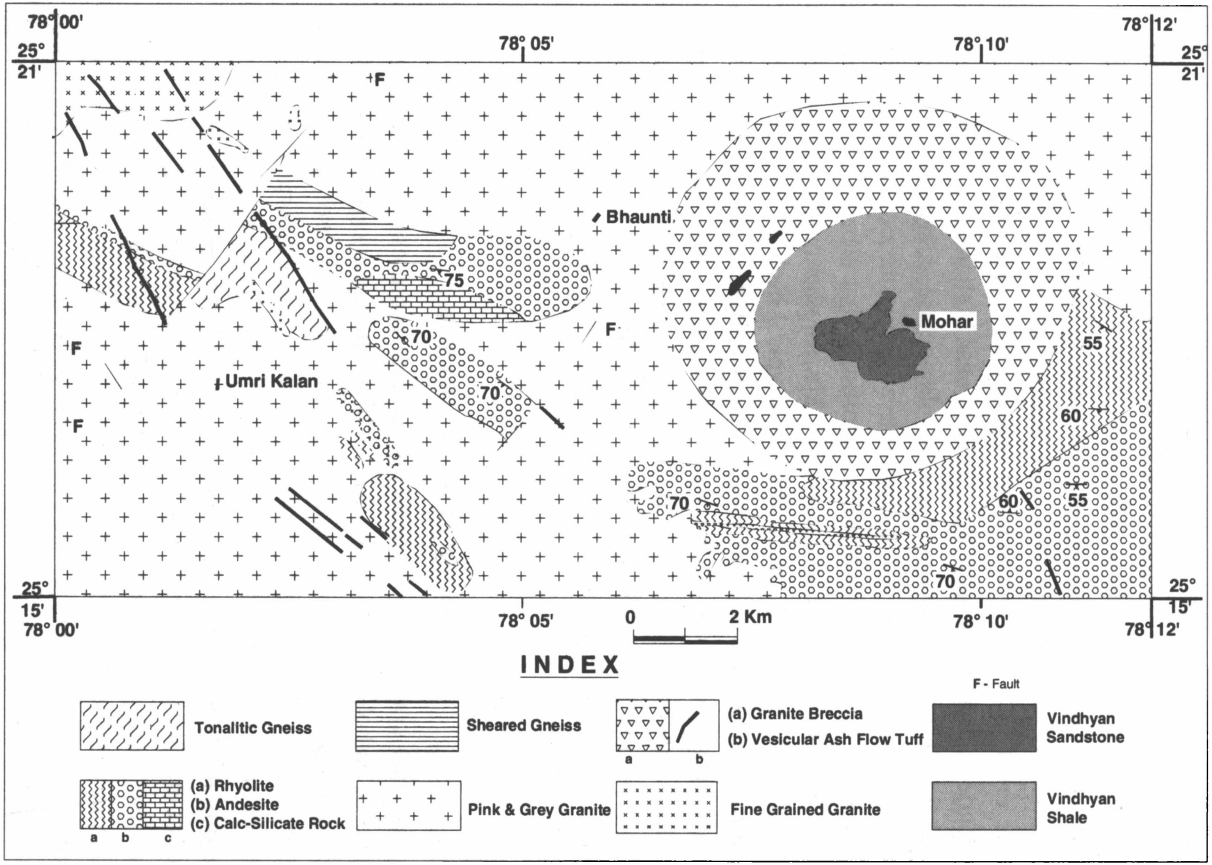

78° 00'
78° 05'
78° 10'
78° 12'
25° 21'
25° 15'
F
Bhaunti
Mohar
Umri Kalan
75
70
70
70
55
60
60
55
70
0
2 Km
INDEX
F - Fault
Tonalitic Gneiss
Sheared Gneiss
(a) Granite Breccia
(b) Vesicular Ash Flow Tuff
Vindhyan Sandstone
(a) Rhyolite
(b) Andesite
(c) Calc-Silicate Rock
a b c
Pink & Grey Granite
Fine Grained Granite
Vindhyan Shale

Fig.3BK-5. Geological map of Mohar cauldron (after Jain et al. 2001).

and depleted in P, Sr, Ti and Ba. The leucogranite bodies are emplaced as shallow level porphyries, dominantly in the marginal part of the plutonic complex. The magma source of the leucogranites is highly fractionated I type with calc alkaline to alkaline composition. The total REE of all the granitic rocks increases from 223-256 ppm in Phase I to 391-721 ppm in Phase II, but decreases in the later phases. The slightly fractionated [$(La/Yb)_N$ = 14 to 17] REE patterns are similar and show a gradual increase in Eu anomaly. Recent Pb-Pb single zircon ages of various granitic phases at Mahoba, Lalitpur and Datia yield an age range of 2400-2550 Ma. These younger events related to granite plutonism indicate widespread cratonisation in Bundelkhand at ~2500 Ma, corresponding to 'granite bloom' in Archaean (Davis and Bleeker, 1999).

*Felsic Volcanic Rocks:* These rocks are associated with the granites at many places such as Mahoba, Bansi, and Simra near Prithipur (Fig.3BK-4). They occur as grey to pink, fine to coarse grained and porphyritic felsic rocks forming conformable layers with gradational boundaries between the different felsic types. They are quartz and felspar porphyries ranging from rhyolite to rhyodacite in composition. They also occur as coarse grained sills and rare dykes. The felsic volcanic suite is involved in extensive shearing, but not in the multiphase folding associated with the enclave suite. Pb-Pb zircon dating of Bansi rhyolites has given an age of 2517±7 Ma, which corresponds to the age of Bundelkhand granite.

*Mohar Cauldron:* Jain et al. (2001) describe a cauldron subsidence structure of 7.5 km diameter near Mohar (3BK-5). The periphery of the cauldron is defined by porphyrite granite breccia. Prophyritic granite is emplaced in the cauldron within a volcano-plutonic sequence consisting of rhyolite, dacite, andesite, microgranite, and trondhjemite. The associated volcanics are mainly vesicular and amygdular ash flow tuffs. Proterozoic Vindhyan sediments occupy the centre of the cauldron. A global comparison of cauldron structures is given in Cole et al. (2005).

## QUARTZ REEFS

The emplacement of NE-SW trending giant quartz reefs (Fig.3BK-6) along brittle to ductile shear zones probably marks the end stage hydrothermal activity related to granitic plutonism. These reefs are spectacular landmarks in the Bundelkhand craton. Eleven major quartz reefs have been recently mapped with a spacing of 12 to 20 km and having lengths of 35-40 km and widths of 50-60 m. Quartz is the essential constituent, with disseminations of limonitised

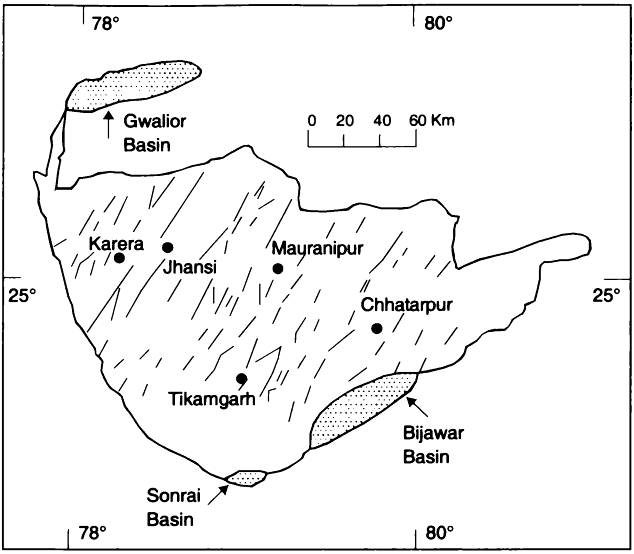


**Fig.3BK-6.** Quartz reefs in Bundelkhand craton (after Sharma and Rahman, 2000).

pyrite, specular hematite, chlorite veins and rare chalcopyrite. Deposits of pyrophyllite and diaspore are noted within these reefs near Mahoba and Palar. These deposits are of hydrothermal origin. Numerous instances of quartz-sericite veins in granites are also recorded. They contain some tourmaline and rare garnet. These veins, earlier mistaken for meta-sedimentary enclaves, are also of hydrothermal replacement origin. Vugs consisting of rock crystal, amethyst and other secondary silica are associated with quartz reefs. Pockets of galena and veins of pyrite-chalcopyrite occur throughout the granite, but they are not of economic importance. The sulphides are also of hydrothermal origin. These features indicate extensive hydrothermal activity associated with Bundelkhand granite.

## MAFIC DYKE SWARMS

A NW-SE trending swarm of mafic dykes is a characteristic feature of Bundelkhand craton (Fig.3BK-7). Some of the dykes have ENE trend, like the prominent Mahoba dyke. The geometry of the main dyke swarms is attributed to E-W shearing stress, developed after cratonisation. Three generations of dykes are noticed on the basis of cross-cutting relations, the last one being probably related to Deccan Trap (Malwa Trap). The dykes are generally a few tens of metres long and about a maximum of 50 m wide. They are discontinuous and follow *en echelon* fractures. They intrude the granites as well as quartz reefs. Most of the dykes are undifferentiated, but some show 'micropegmatite' patches. Most of them are dolerites and gabbros,

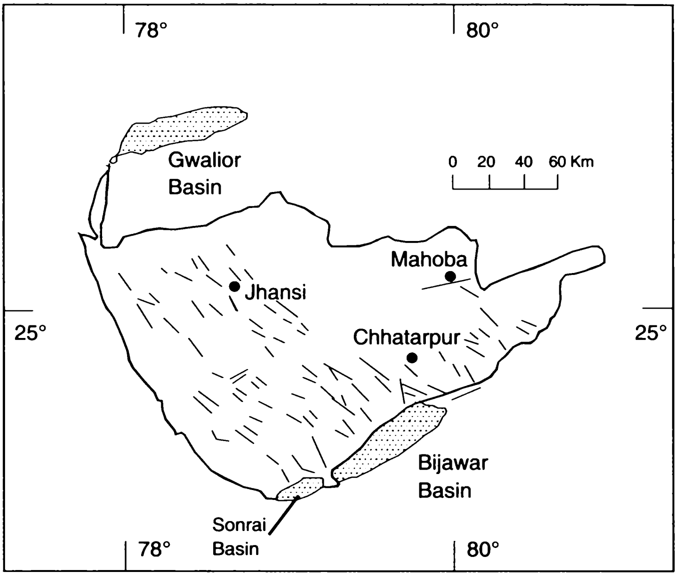


**Fig.3BK-7.** Mafic dykes in Bundelkhand craton (after Sharma and Rahman, 2000).

and some contain orthopyroxene. Locally the mafic minerals show deuteric alteration. Felsite, keratophyre and lamprophyre dykes are rare.

Geochemically the dykes are Fe to Mg rich tholeiites. The dykes are not extensively dated, but there are indications that the dykes may be ~1800 Ma old.

## TECTONIC EVOLUTION

Bundelkhand and Aravalli cratons were traditionally regarded as interlinked, with the Berach granite of Aravalli craton being considered as the equivalent of Bundelkhand granite. Geochemical and geochronological similarities (Table 3BK-1) have reinforced this comparison (*see* GSI, 2004). The separation of two cratons with the evolution of Hindoli and Mahakoshal belts at the cratonic margin, was followed by the evolution of Vindhyan basin. Bundelkhand craton witnessed N-S compression-induced deformation, metamorphism and emplacement of TTG gneisses produced by the partial melting of a garnet amphibolite parental source at 3000-3300 Ma. Widespread collision-related arc magmatism represented by Bundelkhand granite commenced probably at 2700 Ma and culminated at 2500 Ma. The granitic magmatism was associated with extensive hydrothermal activity as seen in the giant quartz reefs containing base metal mineralisation and pyrophyllite-diaspore deposits. The Bundelkhand region was cratonised by 2500 Ma. Rejuvenation of activity in the craton commenced by the emplacement of mafic

**Table 3BK-1.** Geochemical and geochronological comparisons between Bundelkhand and Aravalli cratons

| Features | Bundelkhand craton | Aravalli craton |
|---|---|---|
| Composition of the Gneisses | Tonalite, trondhjemite; highly fractionated REE patterns with depletion of HREE, small negative Eu anomaly | Tonalite, trondhjemite; highly fractionated REE patterns with depletion of HREE, small negative Eu anomaly |
| Composition of the Granitoids | Calc-alkaline, moderately fractionated REE pattern without HREE depletion, large Eu anomaly | Calc-alkaline, moderately fractionated REE pattern without HREE depletion, large Eu anomaly |
| Regional Metamorphism and Deformation | 3.29 Ga (oldest gneissic component; Kuraicha);<br>2.5 Ga (youngest gneissic component; Panchwara) | 3.28-3.3 Ga (oldest gneissic component; Mewar); 2.5 Ga youngest gneissic component, Vali River) |
| Emplacement of Granitoids | ~2.5 Ga | ~2.5 Ga |
| Age of Stabilization | ~2.5 Ga; Sequential development of Mahakoshal and Vindhyan | ~2.5 Ga; Sequential development of Hindoli and Vindhyan |
| Mafic Rocks | Mafic dyke swarms | Mafic volcanics |

dyke swarms, initiation of Hindoli and Mahakoshal supracrustals, followed by marginal sedimentary basins (Bijawar, Gwalior, Sonrai) with mafic volcanism, followed by quiescent conditions of deposition marked by cherts, stromatolitic dolomites, phosphorites and ferruginous beds. The initiation of volcanic and sedimentary rift basins is attributed to plume activity. The least deformed marginal basins indicate tectonic stability of the craton in the quiescent period of 2000 to 1800 Ma in Palaeoproterozoic. The Vindhyan basin and the Satpura and Aravalli belts, swerve around the Chittorgarh syntaxis caused by the promontory of Bundelkhand granite during post-Vindhyan times.

# ARAVALLI CRATON

## INTRODUCTION

Aravalli craton (Fig.3A-1) covers an area of over one lakh (one hundred thousand) km$^2$ encompassing the entire State of Rajasthan, parts of Gujarat and Madhya Pradesh and fringes of Delhi and Haryana. The composite Aravalli craton consists of Mewar craton in the east and Marwar craton in the west, separated by the Phulad Lineament that marks the western boundary of Delhi fold belt. The composite Aravalli craton is bound to the east by the Great Boundary Fault (GBF) and Vindhyan basin that separate the Aravalli from Bundelkhand craton. In the south, the craton abuts against the SONATA (Son-Narmada-Tapti) Lineament that forms the northern boundary of Central Indian Tectonic Zone. In the north, isolated exposures in the Indo-Gangetic Alluvium imply extensions of the craton into the Himalaya, probably via Delhi-Hardwar Ridge. Sparse outcrops in the west of Marwar craton are seen amidst the sands of Thar Desert extending into Pakistan. Aravalli and Bundelkhand cratons are traditionally described together as a single entity in earlier literature, but the similarity is restricted only to the Archaean. Extensive Proterozoic development is only confined to the Aravalli craton. Because of these distinctive geological differences, the Aravalli and Bundelkhand cratons are dealt with separately in this book. Bundelkhand and Aravalli cratons, situated to the north of the great tectonic divide of Central Indian Tectonic Zone, are grouped by some authors under the Northern (or Bundelkhand) Protocontinent of the Indian Shield, to distinguish it from the Southern (or Deccan) Protocontinent consisting of Dharwar, Bastar and Singhbhum cratons.

Aravalli craton is unique in that it does not contain typical greenstone belts or volcanics-dominated belts that are so prominently exposed in the Southern Protocontinent. The craton, on the other hand, is predominantly composed of quartzites, marbles, pelites, greywackes and volcanics that are exposed in the well-known Proterozoic Aravalli-Delhi orogen. The orogen consists of two prominent fold belts of Aravalli and Delhi that are unconformably laid on the Archaean basement of grey gneisses popularly known as the Banded Gneissic Complex (BGC). The Aravalli-Delhi orogen occupies the prominent Aravalli Mountain that is surrounded by plains on all sides. Aravalli craton is also distinguished by the occurrence of the largest felsic volcanic province of India (viz., Malani Igneous Suite), which is the third largest

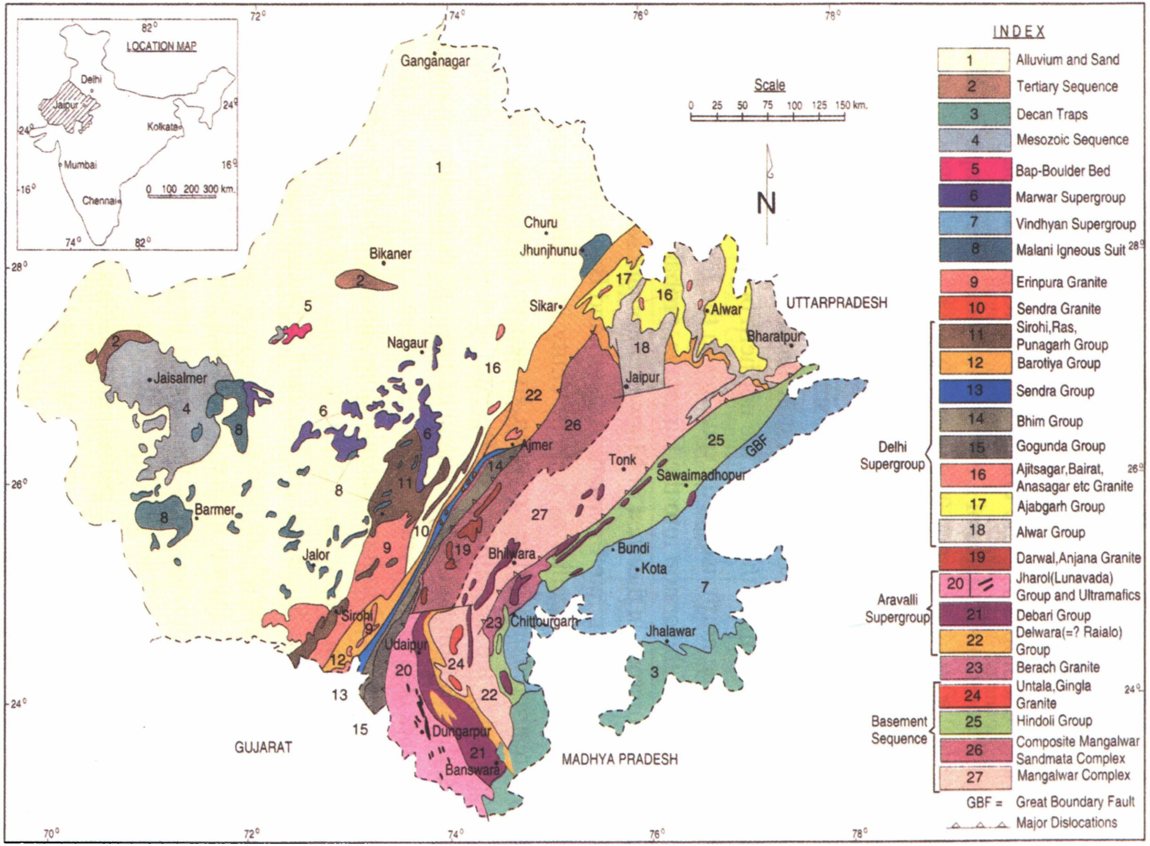

LOCATION MAP
Delhi
Jaipur
Kolkata
Mumbai
Chennai
0 100 200 300 km.
Scale
0 25 50 75 100 125 150 km.
N
Ganganagar
Bikaner
Churu
Jhunjhunu
Sikar
Nagaur
Jaisalmer
Barmer
Jalor
Sirohi
Udaipur
Dungarpur
Banswara
Ajmer
Jaipur
Alwar
Bharatpur
Tonk
Sawaimadhopur
Bhilwara
Bundi
Kota
Chittourgarh
Jhalawar
UTTARPRADESH
GUJARAT
MADHYA PRADESH
GBF
INDEX
1 Alluvium and Sand
2 Tertiary Sequence
3 Decan Traps
4 Mesozoic Sequence
5 Bap-Boulder Bed
6 Marwar Supergroup
7 Vindhyan Supergroup
8 Malani Igneous Suit
9 Erinpura Granite
10 Sendra Granite
11 Sirohi,Ras, Punagarh Group
12 Barotiya Group
13 Sendra Group
14 Bhim Group
15 Gogunda Group
16 Ajitsagar,Bairat, Anasagar etc Granite
17 Ajabgarh Group
18 Alwar Group
19 Darwal,Anjana Granite
20 Jharol(Lunavada) Group and Ultramafics
21 Debari Group
22 Delwara(=? Raialo) Group
23 Berach Granite
24 Untala,Gingla Granite
25 Hindoli Group
26 Composite Mangalwar Sandmata Complex
27 Mangalwar Complex
Delhi Supergroup
Aravalli Supergroup
Basement Sequence
GBF = Great Boundary Fault
Major Dislocations
70°
72°
74°
76°
78°
82°
16°
24°
26°
28°

**Fig.3A-1.** Geological map of Aravalli craton (GSI, 2004, p.65). The map shows 27 lithological units. For differences in lithostratigraphic classification, the text is the guide.

felsic volcanic province of the world. The craton is the home of the only large Pb-Zn-Cu deposit of India (e.g., Agucha, Zawar), besides containing stromatolitic phosphorites and the famous decorative marbles (e.g. Makrana and Ras). Neoproterozoic, Mesozoic and Tertiary sedimentary basins occur to the west of Delhi fold belt in Marwar craton. Extensions of Deccan Volcanic Province into the craton are seen in Saurashtra, Kachchh and Malwa. Dykes of all ages abound in the craton, but have not been studied extensively (Roy et al. 1995).

## Previous Studies

Early geological traverses in the craton were taken by W.T.Blanford in 1877, C.A. Hacket in 1877 and 1881, R.D.Oldham in 1886 and 1893, L.H.D. La Touche in 1902, C.S.Middlemiss in 1921, A.M.Coulson in 1933 and H.Crookshank in 1948. The foundation of Rajasthan geology (earlier called Rajputana) was laid by Gupta (1934) and Heron (1953). They distinguished the gneissic terrain as Banded Gneissic Complex or BGC as the basement on which the later sequences of Aravalli and Delhi "Systems" were laid down with a profound unconformity. Raialo "Series" of marbles and quartzites was considered as separating the Aravalli and Delhi "Systems." They also visualised that in certain sectors the Aravalli and Delhi sequences were highly metamorphosed and migmatised, concomitant with intrusion of granites on large scale. K. Naha and his co-workers carried out extensive structural studies in parts of the craton during 1968-1990 (Naha and Mohanty, 1990). They emphasized the structural similarity between the BGC and Aravalli sequence and supported the views of Heron (1953) that the Aravalli sequence was syntectonically 'granitised' on a large scale to produce BGC. Raja Rao et al. (1971) separated the high-grade schists occurring around Bhilwara as a pre-Aravalli sequence. Gupta et al. (1980, 1997) provided a comprehensive geological framework of the Aravalli craton. They divided the BGC into three pre-Aravalli units of Hindoli Group, Mangalwar Complex and Sandmata Complex that were clubbed together under the Bhilwara Supergroup (>2500Ma), followed by Aravalli Supergroup (2500-2000 Ma), Delhi Supergroup (2000-740 Ma) and Erinpura Granite as well as Malani Igneous Suite. They produced a valuable memoir in 1997 with four geological and four structural maps on 1:2,50,000 scale. Sinha-Roy et al. (1998) concurred with the pre-Aravalli status of Hindoli Group, Mangalwar and Sandmata Complexes of Gupta et al. (1997), but differed from them by excluding the sedimentary basins with Pb-Zn mineralisation (Jahazpur, Rampura-Agucha, Rajpura-Dariba, Pur-Banera, Sawar etc.) from Bhilwara Supergroup and reclassifying them as Aravalli-equivalent belts that evolved as separate pull-apart basins on pre-

Aravalli crust. They also proposed modified stratigraphic schemes for Aravalli and Delhi Supergroups, and evolved models of Proterozoic Wilson cycles in Aravalli craton. Roy and Jakhar (2002) classified the BGC of Heron (1953) into Mewar Gneiss (3300-2500 Ma), followed by Archaean granitoids intruding the Mewar Gneiss as well as forming inliers within Aravalli Supergroup, and TTR (tectonothermally reworked) basement such as Sandmata Complex. They also proposed a different classification for Aravalli and Delhi Supergroups, and favoured riftogenic origin culminating in basin inversion for these supergroups. Regional geophysical data on Aravalli craton are summarised by Reddi and Ramakrishna (1988), Sinha-Roy et al. (1995), Tewari et al. (1998) and Tewari and Vijaya Rao (2003). Major geological syntheses of Aravalli craton published in recent years are by Roy (1988), Sinha-Roy and Gupta (1995), Gupta et al (1997), Sinha-Roy et al. (1998), Paliwal (1999), Kataria (1999), Roy and Jakhar (2002), and GSI (2004).

### Main Components

Aravalli craton is divided here into the following tectono-stratigraphic elements (Fig.3A-2):

1. Archaean Mewar Gneiss with Ancient Supracrustal Enclaves
2. Bhilwara Supergroup (Hindoli Group, Mangalwar Complex and Sandmata Complex)
3. Mineralised Supracrustal Belts (Rajpura-Dariba, Pur-Banera etc)
4. Palaeoproterozoic Aravalli Fold Belt ⎤ Aravalli-Delhi Orogen
5. Mesoproterozoic Delhi Fold Belt ⎦
6. Neoproterozoic Basins (Sirohi, Sindreth, Punagarh)
7. Neoproterozoic Malani Igneous Suite
8. Neoproterozoic Marwar Basins

### Crustal Scale Lineaments

A number of major lineaments (Fig.3A-3) dissect the craton into units that incorporate a combination of tectono-stratigraphic units enumerated above. These are:

(i) Great Boundary Fault bounding the Vindhyan basin to the east and Hindoli belt to the west,

(ii) Banas Lineament or Jahazpur Thrust that separates Hindoli belt from Mangalwar Complex in the north and Mewar Gneiss in the south. This lineament is imaged as a prominent west-dipping zone by deep seismic reflection profiling along the Nagaur-Jhalawar transect,

(iii) Delwara Lineament of Sinha-Roy et al (1998) that marks a gradational

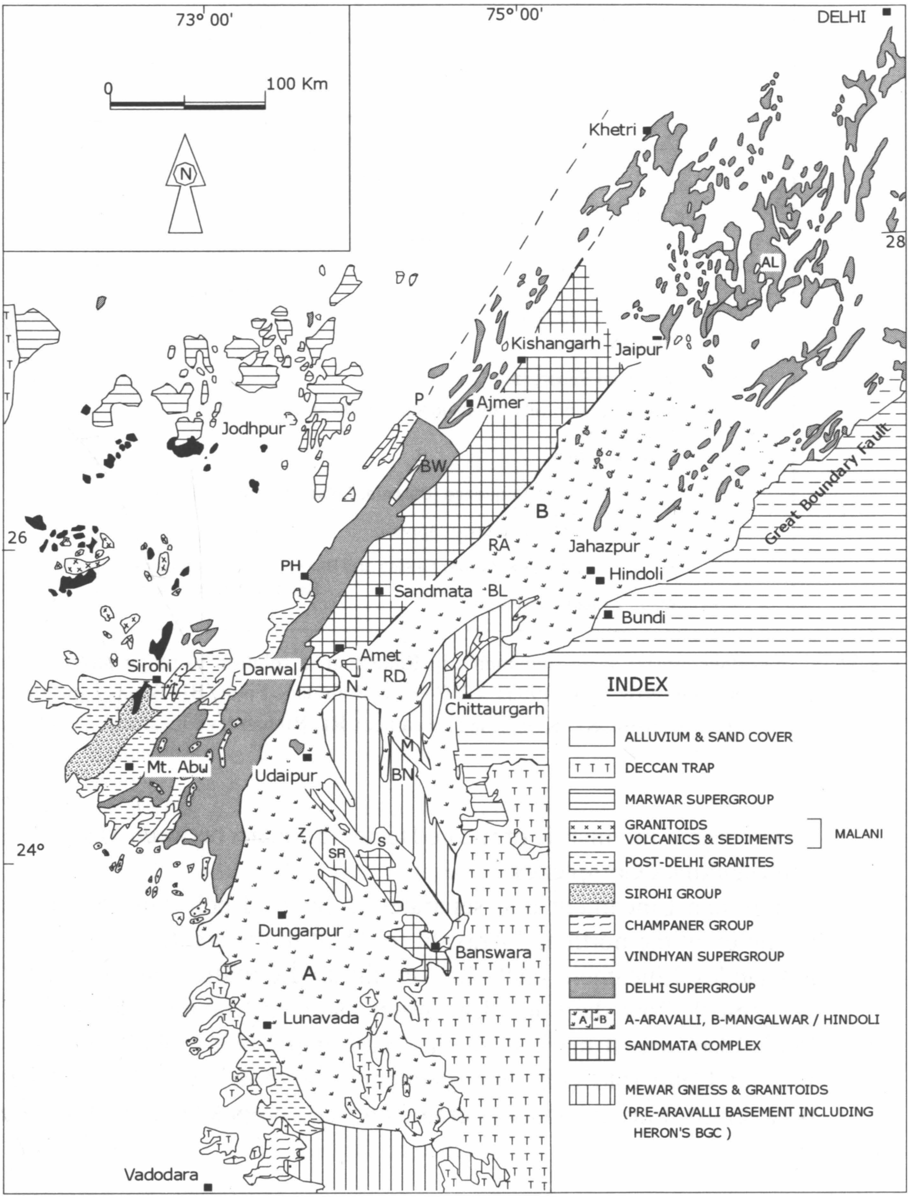

73° 00'
75° 00'
DELHI
0
100 Km
N
28
26
24°
Khetri
AL
Kishangarh
Jaipur
Ajmer
P
Jodhpur
BW
B
RA
Jahazpur
Hindoli
PH
Sandmata
BL
Bundi
Great Boundary Fault
Sirohi
Darwal
Amet
RD
N
Chittaurgarh
Mt. Abu
Udaipur
M
BN
Z
SR
S
Dungarpur
Banswara
A
Lunavada
Vadodara
INDEX
ALLUVIUM & SAND COVER
DECCAN TRAP
MARWAR SUPERGROUP
GRANITOIDS
VOLCANICS & SEDIMENTS
MALANI
POST-DELHI GRANITES
SIROHI GROUP
CHAMPANER GROUP
VINDHYAN SUPERGROUP
DELHI SUPERGROUP
A-ARAVALLI, B-MANGALWAR / HINDOLI
SANDMATA COMPLEX
MEWAR GNEISS & GRANITOIDS
(PRE-ARAVALLI BASEMENT INCLUDING HERON'S BGC )

**Fig.3A-2.** Geological map showing distribution of major stratigraphic units of the Aravalli craton (modified after Roy and Jakhar, 2002, p.40). AL - Alwar; BL - Bhilwara; BN - Bhindar; BW - Beawar; M - Mangalwar; N - Nathdwara; P - Pisangan; PH - Phulad; RA - Rampura-Agucha; RD - Rajpura-Dariba; S - Salumbar; SR - Sarara; Z - Zawar.

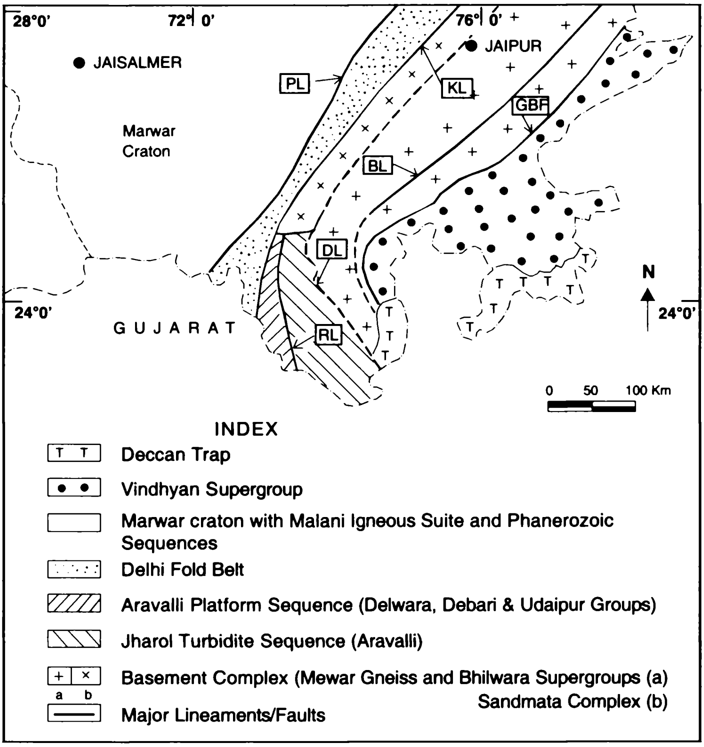

28°0'
72° 0'
76° 0'
JAISALMER
JAIPUR
Marwar Craton
PL
KL
GBF
BL
DL
RL
GUJARAT
24°0'
24°0'
N
0 50 100 Km
INDEX
T T Deccan Trap
● ● Vindhyan Supergroup
Marwar craton with Malani Igneous Suite and Phanerozoic Sequences
Delhi Fold Belt
Aravalli Platform Sequence (Delwara, Debari & Udaipur Groups)
Jharol Turbidite Sequence (Aravalli)
+ × Basement Complex (Mewar Gneiss and Bhilwara Supergroups (a)
a b Sandmata Complex (b)
Major Lineaments/Faults

**Fig.3A-3.** Important crustal scale lineaments in Rajasthan in relation to major stratigraphic units (after Sinha-Roy et al. 1995). GBF-Great Boundary Fault, BL-Banas Lineament, DL-Delwara Lineament, KL-Kaliguman Lineament, RL-Rikhabdev Lineament, PL-Phulad Lineament.

metamorphic-migmatitic or sheared tectonic contact between Mangalwar and Sandmata Complexes,

(iv) Kaliguman Lineament that separates Delhi fold belt from Sandmata Complex in the north and Aravalli fold belt in the south,

(v) Rikhabdev Lineament enclosing an ultramafic-mafic belt (ophiolite?) between shallow shelf and deep-water facies in Aravalli fold belt,

(vi) Phulad Lineament marked by ultramafic-mafic belt (ophiolite?) in the west of Delhi fold belt. The lineament marks the tectonic boundary between Mewar and Marwar cratons of the composite Aravalli craton.

## TECTONO-STRATIGRAPHIC UNITS

### Archaean Mewar Gneiss with Supracrustal Enclaves

### Ancient Supracrustal Enclaves

Numerous enclaves of supracrustal rocks like amphibolite, quartzite, mica schist, crystalline limestone (marble), calc-silicate rock and banded iron

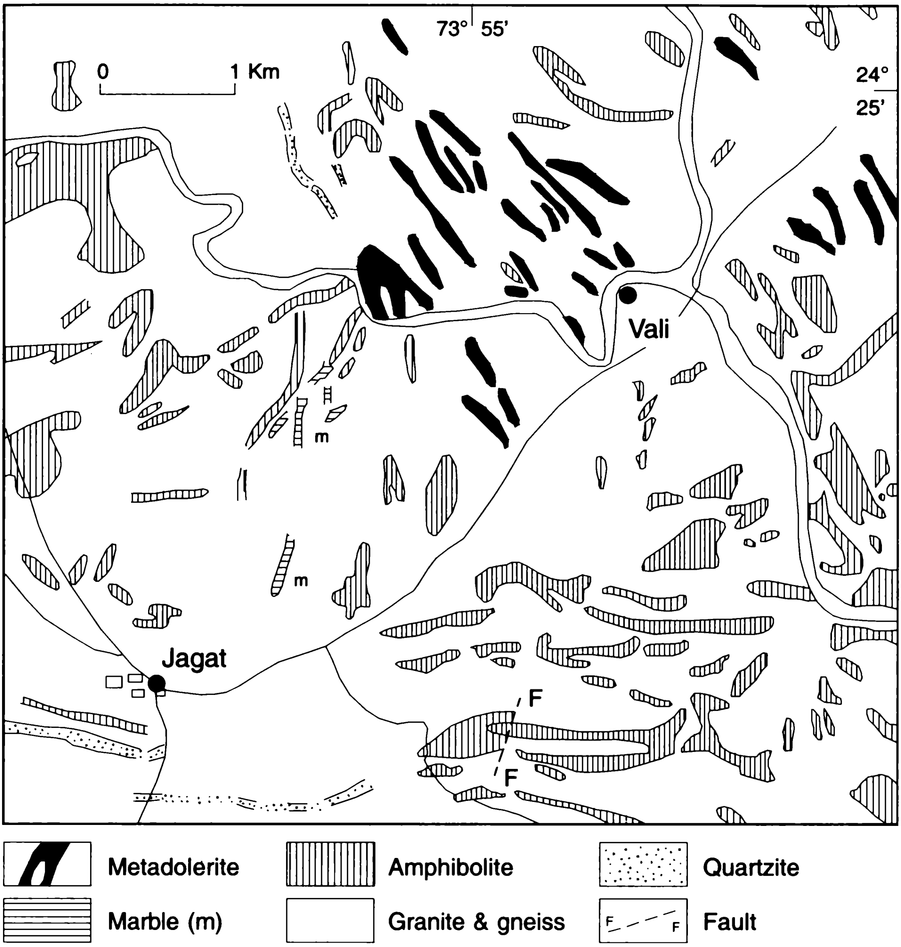

73° 55'
0
1 Km
24°
25'
Vali
Jagat
m
m
m
F
F
Metadolerite
Amphibolite
Quartzite
Marble (m)
Granite & gneiss
Fault
F
F

**Fig.3A-4a.** Geological map of parts of Jagat Group (after Upadhyaya et al. 1992).

formation are widely scattered within the Mewar Gneiss. They are mapped in detail around Jagat area (Fig.3A-4a) and hence called Jagat Group.

*Amphibolites* are schistose consisting of hornblende and plagioclase ($An_{30-40}$), with subordinate quartz. Most amphibolites are tholeiitic basalts, whereas some are basaltic andesites. Amphibolites are generally high in Mg, Ni and Cr, and low in Ti. LREE patterns show slight enrichment, whereas HREE show flat patterns.

*Quartzites* occur as scattered bands in gneiss. A prominent highly folded quartzite is seen in Rakhiawal-Mavli area, where it is intruded by an amphibolite dyke, which gives an Sm-Nd isochron age of 2828±46 Ma. The quartzite is rarely cross-bedded and fuchsitic. It is enriched in Cr and Ni and has a fractionated REE pattern with $(La/Yb)_N = 10$ and $(Gd/Yb)_N = 2$ as well as weak Eu anomaly.

*Carbonate rocks* are low Mg marbles with disseminations of graphite. Their C and O isotopic compositions indicate marine source. They grade into calc-silicate rocks rich in diopside, grossularite, actinolite and sphene.

*Mica schists* are rich in biotite, muscovite and quartz with variable proportions of garnet, staurolite, kyanite and sillimanite. When closely associated with migmatitic gneiss, these schists are felspathic and form paragneisses.

*Banded iron formation* (BIF) occurs as small lenses and discontinuous bands rich in magnetite and quartz, with subordinate garnet and grunerite.

*Ultramafic* enclaves are rare and consist of tremolite-actinolite, talc, chlorite and serpentine. Some may be of komatiitic composition.

The enclave suite (Jagat Group) is interpreted by some as dismembered Archaean greenstone belts. The presence of amphibolites, ultramafic rocks, and BIF in this suite gives credence to such a view, but the lack of coherent greenstone belts associated with such enclaves is inconsistent with such a definition. Further, quartzite, marble and mica schist are not very common associates of greenstone belts. A non-genetic term like 'Ancient Supracrustals' may be more appropriate for these enclaves. The enclave suite may even belong to more than one orogenic cycle, but the present data do not permit differentiation into more than one group of supracrustals.

These supracrustals form part of the BGC of Heron (1953) and occur as enclaves within the Lasaria Formation of the Mangalwar Complex of Gupta et al. (1997). Lasaria Formation extending from Pipalkhunt to Mangalwar comprises migmatitic gneisses with enclaves of mica schist, quartzite, marble and para-amphibolite.

Mohanty and Guha (1995), Sinha-Roy et al. (1998) and GSI (2004) have described two greenstone-type sequences from Lawa Sardargarh and Parasali, called Sawadri and Tanwan Groups. Similar greenstones are also reported from Gujarat. Sawadri Group consists of chert, carbonate, tuff, fuchsite quartzite and komatiite with relict spinifex texture. The lithological association is regarded as typical of 'older' or 'primary greenstones'. The ultramafics intruded by pegmatite contains emerald. Tanwan Group consists of amygdaloidal amphibolite, marble, calc-silicate rock and garnet-sillimanite schist (meta-greywacke?). The metalavas are described as tholeiitic basalts, andesites and hawaiites. This lithological ensemble is comparable to 'younger' or 'secondary greenstones'. The greenstone sequences of both types are intruded by tonalitic to granodioritic gneisses and granites (Ran Igneous Complex). The stratigraphic status of these greenstone sequences is controversial. Gupta et al. (1997) have included them under the younger and more metamorphosed Aravalli Supergroup (Kankroli and Dovda Groups), and many authors agree with this correlation.

### Mewar Gneiss

Heron (1953) called all the grey gneisses, migmatites and granitoids of the Mewar region as Banded Gneissic Complex (BGC). Subsequent work has shown that the BGC included components of diverse ages with differences in basement-cover relationship. Gupta (1934) labelled BGC-I for those gneisses that form clear basement to Aravalli Supergroup and BGC-II for those that are reworked extensively during later deformational events. BGC-I roughly corresponds to the terminology of Mewar Gneiss coined by Roy (1988a). This terminology is consistent with the Code of Stratigraphic Nomenclature, unlike BGC, which has no specific stratigraphic status and has only the sanction of long usage in its support. Mewar Gneiss forms an incontrovertible basement to Aravalli Supergroup and corresponds to the migmatites and gneisses of Lasaria Formation of Mangalwar Complex of Gupta et al. (1997).

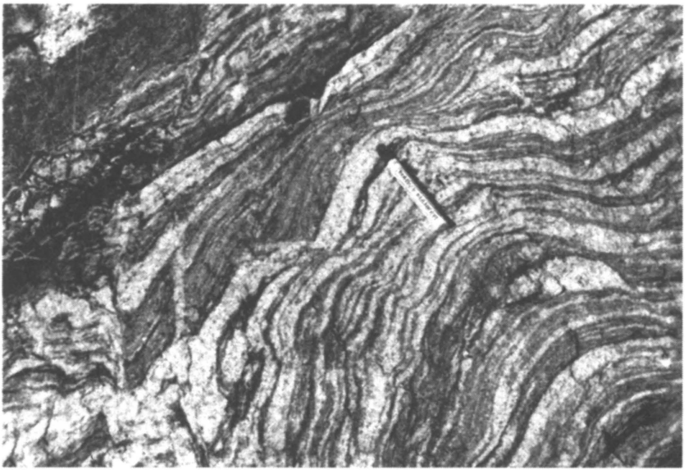


**Fig.3A-4b.** Banded biotite gneiss belonging to Mewar Gneiss (from Roy and Jakhar, 2002).

The three principal components of Mewar Gneiss are:

(i) Basement TTG gneisses least affected by later deformation and metamorphism.

(ii) Basement granitoids intruding the TTG gneisses (e.g., Untala and Gingla granites), and

(iii) Basement granitoids occurring as inliers within the Aravalli fold belt (e.g. Sarara, Mando and Ahar River granites).

A brief description of these components follows:

*Basement TTG gneisses:* The basement gneiss is best exposed between Mavli and Pipalkhunt. The main rock type is the banded migmatitic biotite gneiss of tonalite-trondjhemite-granodiorite (TTG) composition (Fig.3A-4b). The main TTG gneiss itself contains enclaves of banded biotite gneiss suggesting the multiphase development of basement gneisses. Structural studies indicate four generations of folding $F_1$ to $F_4$. Large structure of the gneisses is an upright $F_2$ fold on NNE axial plane with curvilinear axis having variable plunge. $F_1$ fold with upright axial plane is common in the enclave suite. Later $F_3$ and $F_4$ folds are not fabric-forming and may be correlated with structures in the cover rocks.

TTG gneiss is composed of quartz, plagioclase ($An_{20-30}$), microcline, biotite, muscovite, garnet and rarely, hornblende. Tourmaline, zircon, apatite and sphene are common accessories. The gneisses belong to low-alumina type with calc alkaline trend. Trace elements like Zr, Nb and Y show enriched LREE patterns with weak Eu anomaly.

Single zircon and Sm-Nd isochron ages of TTG gneisses of Jagat and Jhamarkotra areas are in the range of 3300-2900 Ma. These ages are consistent with the ~2800 Ma date of Mavli amphibolite dyke that intrudes Jagat Group.

*Basement granitoids:* Such granites in the greenstone terrain of Australia are called ‘external granitoids’ as they occur away from or at the margins of supracrustal belts. There are a number of late Archaean granitoids intruding the Mewar Gneiss viz. Untala and Gingla granites. They show either crosscutting relation to gneissic banding or have gradational contact with the gneisses. An idea was floated that enclaves of amphibolites, ultramafics and BIF are confined to TTG gneisses, whereas quartzites, marbles and pelites were confined to basement granitoids, but this could not be confirmed on a regional scale.

*Untala granite* (Fig.3A-5) occurring close to Untala (Vallabhnagar) covers an area of 30x10 $km^2$ and consists of early diorite-tonalite-trondhjemite and late pink to grey granite grading into granodiorite. Several enclaves of banded gneisses are seen in the contact zone and the gneisses are criss-crossed by granitic veins. The trondhjemite gneiss yields a zircon age of ~2900 Ma, whereas the pink granite is dated at ~2500 Ma.

*Gingla granite* occurring close to Jaisamand Lake (Dhebar Lake) is partly migmatitic and partly granitic. The migmatite has tonalite-trondhjemite composition, whereas the granite has granite-adamellite composition. The contact with surrounding gneisses is gradational. The granite encloses rafts of biotite gneiss and orthoamphibolite. Similar to Untala granite, the Gingla granite gives ages of ~2800 Ma and ~2600 Ma for the older and younger components.

*Basement inliers:* These inliers correspond to the ‘internal granitoids’ (those occurring within supracrustal belts) in Australia, but for the difference that these granites are basement to the cover rocks of Aravalli Supergroup.

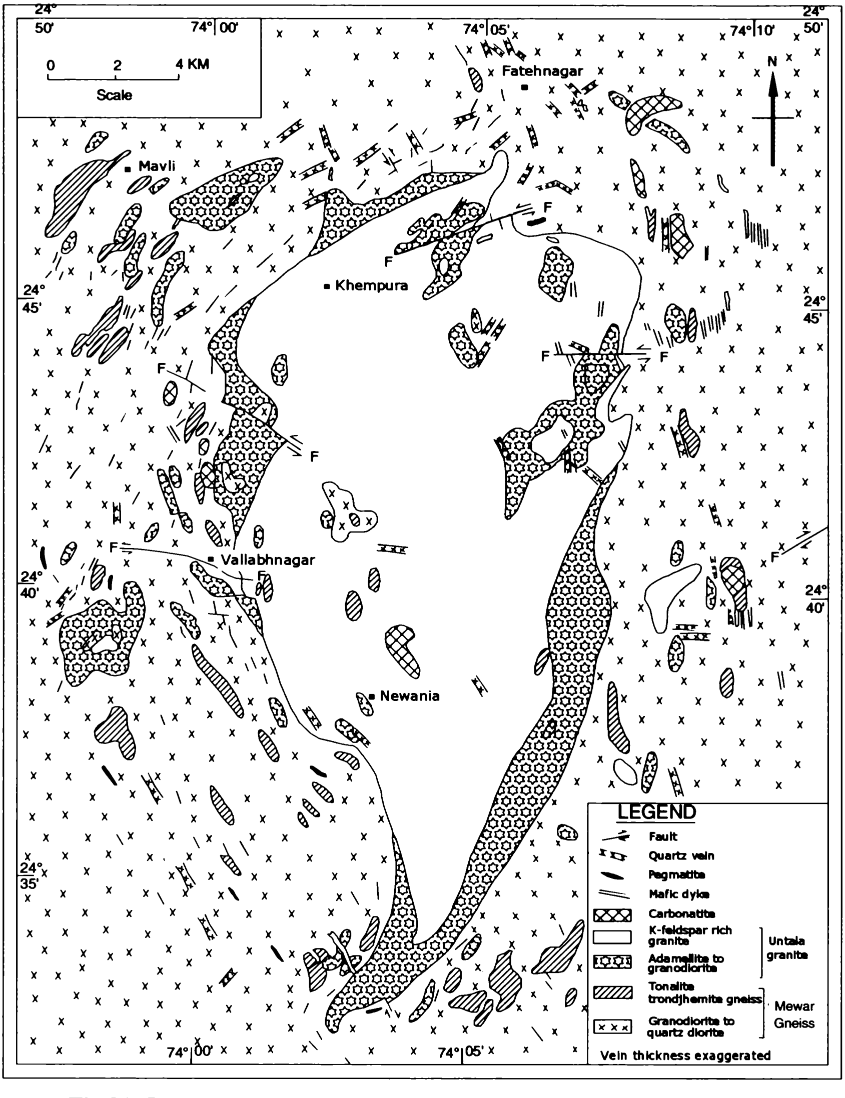

24° 50'
74°|00'
0 2 4 KM
Scale
74°|05'
74°|10'
24° 50'
N
Fatehnagar
Mavli
Khempura
F
24° 45'
24° 45'
Vallabhnagar
24° 40'
24° 40'
Newania
24° 35'
74°|00'
74°|05'
LEGEND
Fault
Quartz vein
Pegmatite
Mafic dyke
Carbonatite
K-feldspar rich granite
Adamellite to granodiorite
Untala granite
Tonalite trondjhemite gneiss
Granodiorite to quartz diorite
Mewar Gneiss
Vein thickness exaggerated

**Fig.3A-5.** Geological map of Untala granite (from Roy and Jakhar, 2002).

*Sarara inlier* is the most prominent one covering an area of 50x20 km$^2$, situated to the south of Zawar Mines. The oval body that trends NW-SE is rimmed by the basal Aravalli rocks with an erosional unconformity. Migmatites are the most common, containing enclaves of Jagat Group. *Mando Inlier* covering 30x10 sq. km and trending NW-SE occurs to the SW of Sarara and to the east of Dungarpur. The geological setting is similar to that of Sarara inlier. *Bagdunda dome* (Fig.3A-6) is an elongate gneissic dome found within Jharol Group of Aravalli Supergroup. It is a basement dome rimmed by the quartzite-metabasalt association of the basal Aravalli sequence, although some authors equate the rim sequence with Jagat Group. Similarly, *Titri or Panda granite*

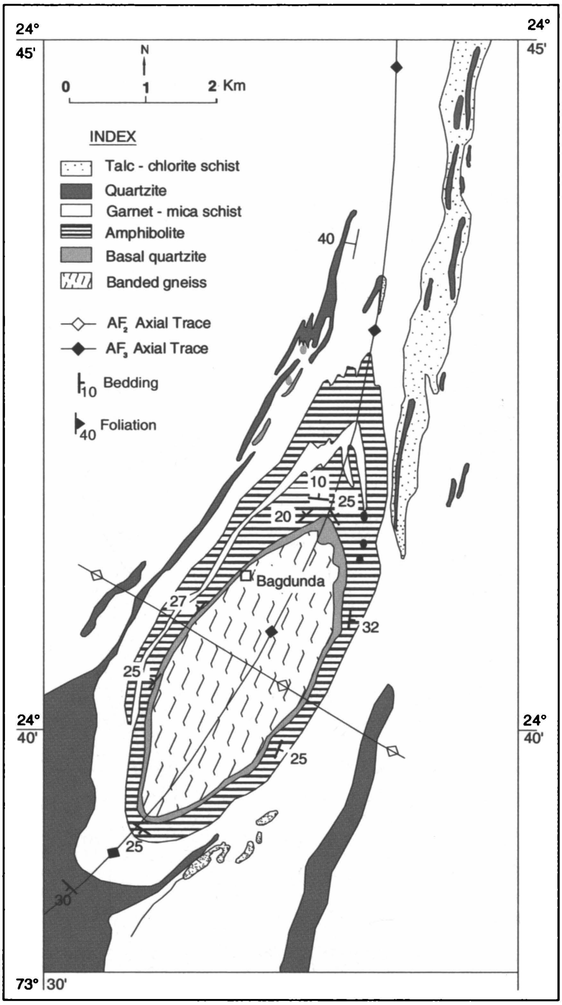

24°
45'
24°
45'
N
0
1
2 Km
INDEX
Talc - chlorite schist
Quartzite
Garnet - mica schist
Amphibolite
Basal quartzite
Banded gneiss
AF₂ Axial Trace
AF₃ Axial Trace
10 Bedding
40 Foliation
40
10
25
20
Bagdunda
27
32
25
24°
40'
24°
40'
25
25
30
73° 30'

**Fig.3A-6.** Geological map of Bagdunda dome (after B.L. Sharma et al. 1988).

rimmed by pebbly quartzite and limestone of Aravalli sequence is another basement dome. *Ahar River granite (Udaipur Granite)* is an irregular body of granite situated close to Udaipur. The granite was originally regarded as intrusive into Aravalli supracrustals, but now is known to be basement. The granite ranges in composition from normal granite to granodiorite. Single zircon dates of the granite are about 2560 Ma and 2020 Ma for the older and younger components. Similar basement granite is *Udaisagar granite* that is a laterally compressed laccolith trending E-W and consists of older pink granite and younger leucogranite.

*Petrogenesis:* The Archaean granites and gneisses of the craton are believed to have evolved in two stages. The first stage is the generation of amphibolite from peridotitic mantle and the second stage is the partial melting of amphibolites to produce TTG gneisses and younger granitoids. The K-rich granitoids are probably derived from the partial melting of gneisses followed by fractionation. Some of these granites also may have had contributions from basic crust, besides that of gneisses. Detailed petrogenetic modelling on regional scale in the craton has not been attempted yet.

Synthesis of available geochronological data shows earliest orogenic cycle in the craton spanned the period from 3300 Ma to 2900 Ma. This orogenic event was followed by a major thermal episode at ~ 2500-2600 Ma that marked widespread cratonic stabilisation.

### Bhilwara Supergroup

Banded Gneissic Complex (BGC) of Heron (1935) included a series of gneisses and granulites that were considered as basement to the Aravalli-Delhi orogen. Later geological synthesis after extensive mapping by the Geological Survey of India (Gupta et al. 1980) led to the division of BGC, renamed as Bhilwara Supergroup, into three tectono-stratigraphic units (Fig.3A-7), viz.

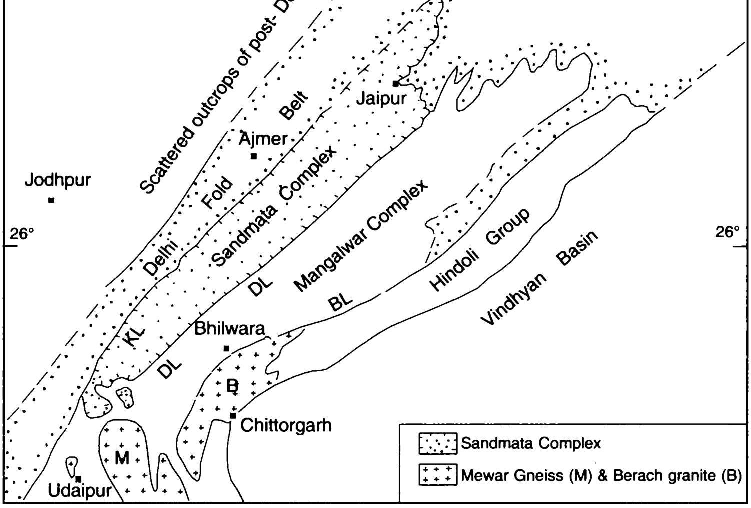

74°
76°
78°
0
75 km
N
28°
28°
DELHI
Jodhpur
26°
26°
Scattered outcrops of post- Delhi rocks
Delhi Fold Belt
Ajmer
Jaipur
Sandmata Complex
Mangalwar Complex
Hindoli Group
Vindhyan Basin
DL
BL
KL
DL
DL
Bhilwara
B
Chittorgarh
M
Udaipur
Sandmata Complex
Mewar Gneiss (M) & Berach granite (B)

**Fig.3A-7.** Sketch map of Bhilwara Supergroup and Delhi fold belt (after Roy and Jakhar, 2002, p.108). Isolated mineralised belts are shown in Fig.3A-11. BL-Banas Lineament, DL-Delwara Lineament, KL-Kaliguman Lineament.

Hindoli Group, Mangalwar Complex together with Isolated Mineralised Belts, and Sandmata Complex. The mutual stratigraphic relations between these units as well as with the Aravalli-Delhi orogen are controversial. These units are described below along with their stratigraphic problems.

## Hindoli Group

Hindoli Group consisting essentially of turbidites and minor volcanics is named after Hindoli near Bundi. These rocks occur in an arcuate belt over a length of about 400 km and variable width of 10 to 50 km, fringing the Mesoproterozoic Vindhyan basin (Fig.3A-8). The contact with the Vindhyan is both faulted and unconformable as seen near Chittorgarh (Chittaurgarh). The contact with the gneissic complex is either locally faulted or a "migmatite

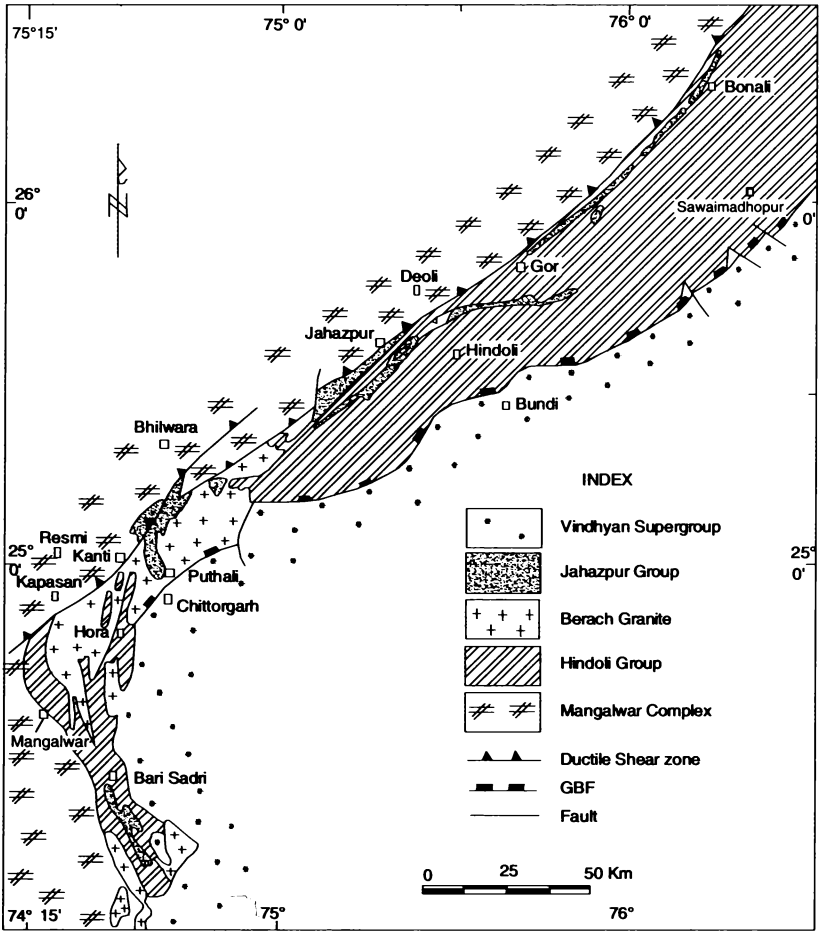

75°15'
75° 0'
76° 0'
Bonali
26° 0'
N
Sawaimadhopur
0'
Gor
Deoli
Jahazpur
Hindoli
Bundi
Bhilwara
Resmi
25° 0'
Kanti
Kapasan
Puthali
Chittorgarh
Hora
Mangalwar
Bari Sadri
25° 0'
74° 15'
75°
76°
INDEX
Vindhyan Supergroup
Jahazpur Group
Berach Granite
Hindoli Group
Mangalwar Complex
Ductile Shear zone
GBF
Fault
0
25
50 Km

**Fig.3A-8.** Geological map of Hindoli belt (after Sinha-Roy et al. 1998). GBF=Great Boundary Fault.

front". Hindoli belt is covered by Deccan Trap of Malwa Plateau in the south. Hindoli Group has been variously equated with Gwalior Group of Bundelkhand craton, pre-Aravalli sequence within Bhilwara Supergroup and lower part of Aravalli Supergroup (Delwara Group). Rhyodacite of Hindoli Group gives zircon concordia age of 1854±7 Ma indicating that it is homotaxial with a part of the Aravalli sequence.

Hindoli Group consists mainly of greywackes and phyllites, besides minor cross-bedded quartzite, dolomitic limestone and algal dolomite. Thin horizons of oligomictic as well as polymictic conglomerate occur at different stratigraphic levels. Turbiditic greywackes preserve ripple marks, load casts and cross bedding. Recently, a suite of volcanics and volcaniclastics are reported from the greywacke sequence. The volcanics are essentially tholeiitic basalts, basaltic andesites, dacites and rhyodacites. The rocks are metamorphosed mainly in greenschist facies grading locally into amphibolite facies. The phyllites are converted to mica schists containing garnet and staurolite, as well as andalusite that formed due to later thermal impress. Hindoli Group is classified into three facies, viz. turbidite facies of greywackes, shelf facies of arenite and carbonate, and volcanic facies. These facies are interpreted by some authors to indicate continental margin sequence coupled with a volcanic arc.

### *Berach Granite*

Berach Granite, correlated by earlier workers with Bundelkhand granite, covers an extensive area to the west of Chittorgarh (Fig.3A-8). The granite occurs within as well as at the borders of the Hindoli belt. It consists of two phases, an older foliated granodiorite to adamellite, and a younger phase of grey granite to leucogranite. Both phases of granite are intruded by pegmatite, aplite and leucogranite. Rb-Sr isochrons and single zircon dates of this granite show a range of ages from 2450 to 2610 Ma. The contact relation between Berach granite and Hindoli Group is controversial. Those who believe that it is basement cite the presence of paleosol, absence of xenoliths and apophyses, and persistence of quartzite-dolomite-phyllite at the contact of granite and Hindoli belt. Those who favour intrusive origin cite the evidences of felspathisation of schists at the contact, presence of meta-sedimentary enclaves in granite and tongues of granite intruding the belt. These ambiguous field relations may result from differing nature of contacts of the two phases of Berach granite with the Hindoli belt. Recently, *Jahazpur granite*, correlated with Berach granite, is regarded as intrusive into Hindoli Group.

Many authors have correlated Hindoli belt with the Mahakoshal belt of Central India. Both the belts are probably interlinked beneath the cover of Deccan Trap and form part of Satpura mobile belt (Fig.3BK-2). Mahakoshal belt has an age range of 1600-1850 Ma and Hindoli belt is about 1850 Ma old. This age coincides with the Aravalli orogeny, although depositional age of Aravalli Supergroup is around 2200 Ma.

*Hindoli dolerites* occur as sills and dykes within the metasediments of Hindoli and Jahazpur Groups. Similar but younger dykes intrude Ranthambhor Group. Patches of dolerite and amphibolite are also found within Berach granite.

### Mangalwar Complex

Mangalwar Complex encompasses the vast stretch of varied gneisses occurring between the Banas Lineament bounding the Hindoli belt in the east and the Delwara Lineament bounding Sandmata Complex in the west (Fig.3A-7). The complex is divided into Lasaria, Potla, Suwana and Kekri Formations by Gupta et al. (1997). Lasaria Formation occurring in the south consists mainly of migmatites and composite gneisses, with enclaves of tremolite-talc-chlorite schist, amphibolite, quartzite and crystalline limestone. This formation, having the grand unconformable contact with the Aravalli Supergroup, corresponds to Mewar Gneiss and BGC-I described earlier and is not included under Mangalwar Complex in this book. Potla Formation comprises garnet-staurolite-biotite schist, kyanite-sillimanite-mica schist and felspathic biotite schist with subordinate quartzite, crystalline limestone, amphibolite and migmatitic gneisses. Suwana Formation covering a small swathe within Potla Formation near Bhilwara is essentially made of migmatised amphibolites with minor bands of garnet-biotite-kyanite schist, calc-silicate rocks and quartzite. Potla and Suwana Formations constitute the bulk of metasediments of Mangalwar Complex. The contact between the orthogneisses of Lasaria Formation (BGC-I) and migmatitic gneisses of Potla Formation (BGC-II) is gradational due to pervasive migmatisation. Kekri Formation, exposed extensively in the north and occurring as lenses within Potla Formation, consists of migmatites and composite gneisses, and contains enclaves of garnet-biotite schist and calc-silicate rocks. Swathes of lithic ensemble called variously as Ranthambhor 'Group' and Rajmahal 'Formation' (Rajmahal Quartzite) are seen within Kekri Formation in the north. These swathes occur in a setting similar to the large swathe of Suwana Formation that is enclosed within the major Potla Formation.

Ranthambhor Group consists of a series of quartzites and phyllites intruded by sills of dolerite seen near Sawai Madhopur. Rajmahal Formation is a massive quartzite attaining a width of about three km and having pebbly horizons at the contact with the mica schists of Kekri Formation. There is a dispute as to whether the pebble beds are sedimentary or tectonic breccias. Potla, Suwana and Kekri Formations as well as Ranthambhor Group and Rajmahal Quartzite comprise the BGC-II of Gupta (1934). Of these, only the Kekri Formation has a dominant component of orthogneisses. The contact between Kekri and Potla Formations is also gradational.

There is a problem of the stratigraphic status of various swathes within the major formations of Mangalwar Complex. The swathes of Suwana Formation, Ranthambhor Group and Rajmahal Quartzite appear to be part of Mangalwar supracrustal sequence. The concentration and dominance of specific lithological suites within the swathes have distinguished them from the enclosing formations consisting of a vast expanse of garnet-biotite schists and migmatitic gneisses. There is, however, the problem of mineralised supracrustal belts (Rampura-Agucha, Rajpura-Dariba, Pur-Banera etc) that rest with major unconformity on Mangalwar Complex. These belts form a distinctively younger suite. The swathes like Suwana Formation are metamorphosed and deformed together with Mangalwar Complex, with consequent erasure of contact relationships. The status of some of these swathes and mineralised belts may have to be reassessed depending on the new information pouring in.

In the model of linkage of Aravalli craton with the CITZ (Fig.3BK-2), Mangalwar Complex may correlate with Betul Group that contains comparable mica and base metal occurrences. Geochronological data are rare for Mangalwar Complex, but may correspond to the time span of 2600-2900 Ma during which Mewar Gneiss would have thermo-tectonically reconstituted into Mangalwar Complex along with the supracrustal swathes. Bhilwara meta-sedimentary suites (Potla and Suwana Formations) may have also formed at the same time span (2600-2900 Ma), but limited isotopic data (1700 and 950 Ma, Buick et al. 2006) have hampered reasonable correlation.

## Sandmata Complex

The boundary between the granulite belt of Sandmata Complex and the gneissic terrain of Mangalwar Complex is marked by Delwara Lineament. The contact appears to be gradational, marked by amphibolite-granulite facies transition. Sandmata Complex (Fig.3A-9) consists of large areas of migmatitic gneisses in amphibolite facies containing enclaves similar to those of Mangalwar Complex (called Tanwan Group) as seen at Amet. There are also enclaves that are similar to those in basement gneisses (Mewar Gneiss) called Sawadri Group. The controversial status of these enclaves has been mentioned already under the section on Ancient Supracrustals. The granulites are represented by charnockites and enderbites, basic granulites (mainly garnet-two pyroxene granulites). Amphibolites, norites and dolerites are also seen. Pelitic granulites

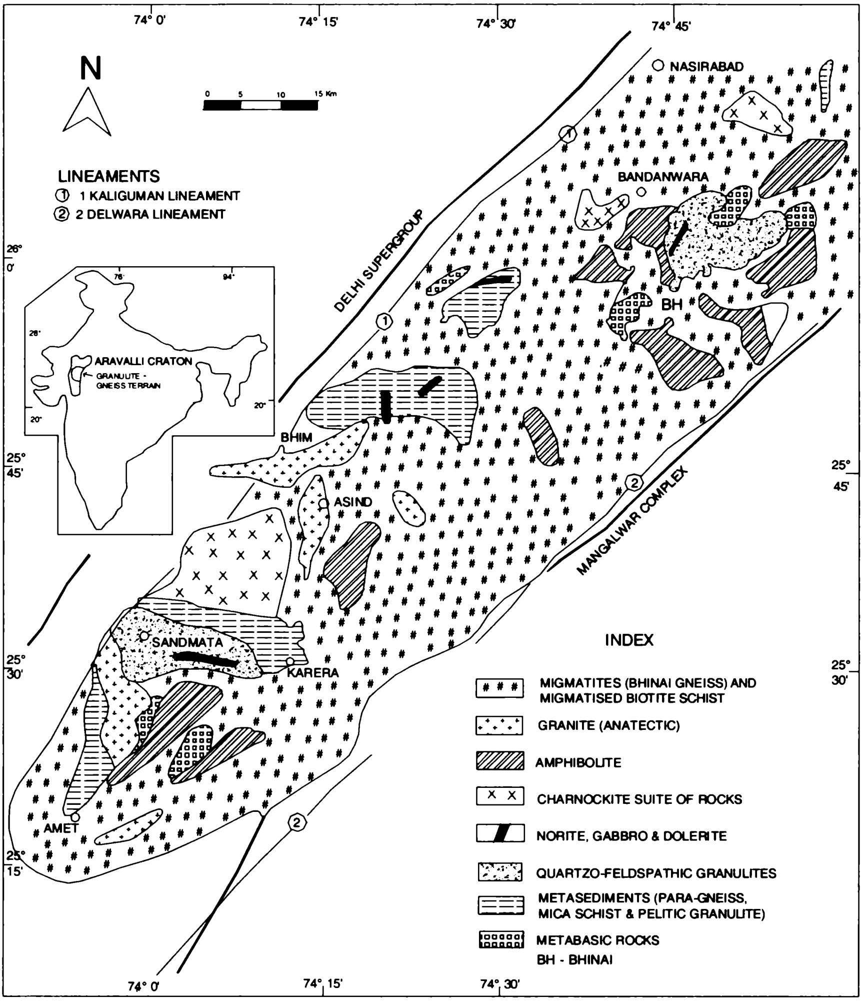

74° 0'
74° 15'
74° 30'
74° 45'
N
0 5 10 15 Km
LINEAMENTS
① 1 KALIGUMAN LINEAMENT
② 2 DELWARA LINEAMENT
26° 0'
25° 45'
25° 30'
25° 15'
78°
94°
28°
20°
ARAVALLI CRATON
GRANULITE - GNEISS TERRAIN
NASIRABAD
BANDANWARA
BH
DELHI SUPERGROUP
MANGALWAR COMPLEX
BHIM
ASIND
SANDMATA
KARERA
AMET
INDEX
MIGMATITES (BHINAI GNEISS) AND MIGMATISED BIOTITE SCHIST
GRANITE (ANATECTIC)
AMPHIBOLITE
CHARNOCKITE SUITE OF ROCKS
NORITE, GABBRO & DOLERITE
QUARTZO-FELDSPATHIC GRANULITES
METASEDIMENTS (PARA-GNEISS, MICA SCHIST & PELITIC GRANULITE)
METABASIC ROCKS
BH - BHINAI

**Fig.3A-9.** Geological map of Sandmata Complex (after Gyani and Kataria, 2000, p.278).

are garnet-sillimanite-felspar gneisses and cordierite-hypersthene-spinel-kornerupine gneisses reported from SE Rajasthan and Gujarat (Sharma, 1990; Srikarni et al. 2003).

The contact between the granulites and gneisses is sheared and therefore interpreted as tectonic, with the granulites exhumed from deeper levels as klippen. This also corroborated by massive charnockites enclosing angular blocks of banded gneisses in Masuda area (Fig.3A-10), where younger quartzo-felspathic veins cut across the host and the enclave. Further, there are no reports of incipient charnockites developed from gneisses in the transition zone.

Granitoids are very common throughout the complex, like the Gyangarh-Asind bodies, otherwise known as Nandwara granitoids. Many granitoids remain

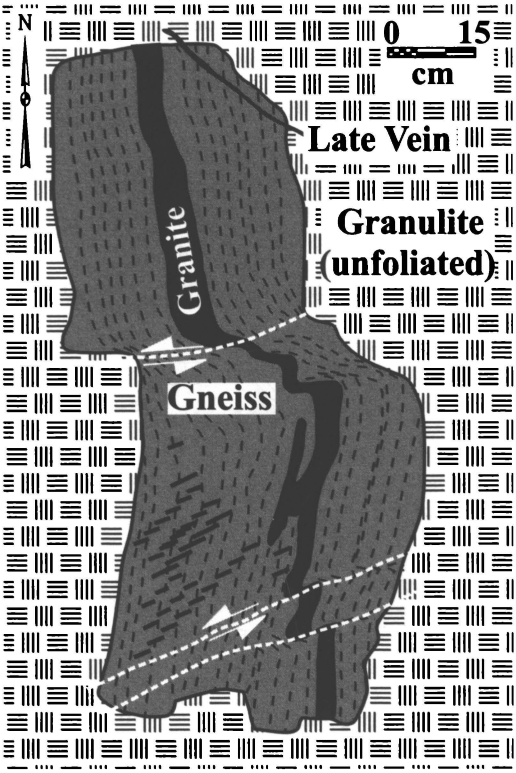


**Fig.3A-10.** Enclave of banded gneiss in massive charnockite (Srivastava, 2001).

undifferentiated. Anjana (Amet) granite, Kanor granite and Chhota Udepur granite are exposed in the southern part.

The age of Sandmata Complex is not well constrained. Granitoids of Masuda and Badnor areas have dates around 2830 Ma that correspond to the age of amphibolites from Nandwara. These dates are similar to the age of Mewar Gneiss, thereby indicating the survival of basement components in the reconstituted complex. U-Pb dates of charnockite-enderbite, Pb-Pb date of galena from Agucha and zircon ages of granites within the complex (Amet, Darwal) are about 1700-1900 Ma that corresponds to the Aravalli orogenic event. The contact of Sandmata Complex with Aravalli Supergroup in the south is controversial and will be discussed in the section on Aravalli fold belt.

### Mineralised Supracrustal Belts

Many subparallel belts of arenite-pelite-carbonate association with black shales and BIF, hosting important lead-zinc mineralisation in the craton, are seen unconformably overlying Mangalwar Complex and Hindoli Group. Heron (1953) correlated them with Raialo 'Series'. Gupta et al. (1997) included them under the youngest unit of pre-Aravalli sequence of Bhilwara Supergroup, and gave stratigraphic status of 'group' to the sequences in each isolated belt (e.g., Jahazpur Group, Pur-Banera Group etc). Sinha-Roy et al. (1998) described them as Aravalli-equivalent isolated cover sequences deposited in pull-apart basins within Mangalwar Complex. These have been correlated with the Zawar Formation of Udaipur Group in this book following Roy and Jakhar (2002). The age of these belts is reckoned as Palaeoproterozoic (~1800 Ma) based on limited isotopic data. All these belts have undergone multiphase deformation and regional metamorphism up to amphibolite facies. Important belts are those of Jahazpur, Sawar, Pur-Banera, Rajpura-Dariba, Rampura-Agucha and Bhindar (Fig.3A-11). These mineralised supracrustal belts are described below:

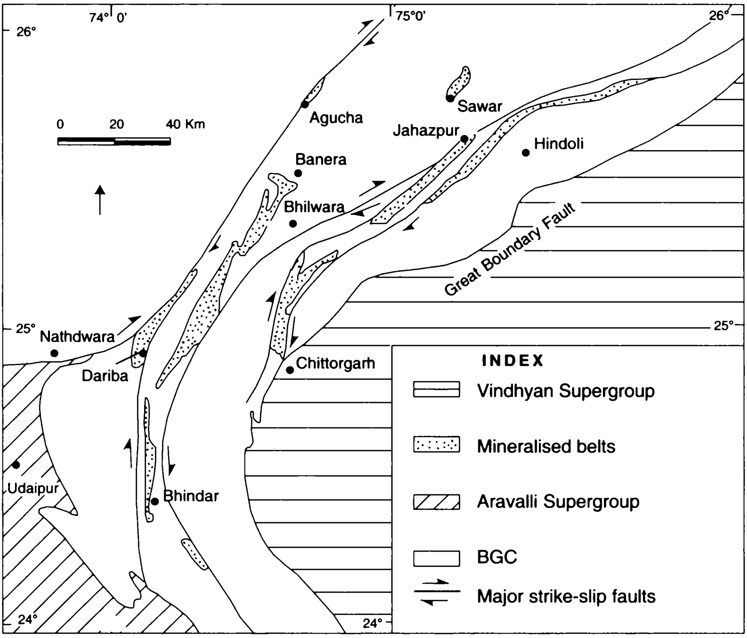

74° 0'
75°0'
26°
26°
0 20 40 Km
Agucha
Sawar
Jahazpur
Hindoli
Banera
Bhilwara
Great Boundary Fault
25°
Nathdwara
Dariba
Chittorgarh
25°
Udaipur
Bhindar
24°
24°
INDEX
Vindhyan Supergroup
Mineralised belts
Aravalli Supergroup
BGC
Major strike-slip faults

**Fig.3A-11.** Mineralised sedimentary belts within BGC (after Sinha-Roy et al. 1998).

*Jahazpur Belt*

Jahazpur Group, named after Jahazpur town by Bradshaw (1928), occurs in two linear sub-belts of about 70x3 km$^2$ each (Fig.3A-12 a&b), and are called the western and eastern sub-belts (Malhotra and Pandit, 2000). The western sub-belt is the type area for Jahazpur Group that contains basal conglomerate and gritty quartzite, grey phyllite, dolomite with BIF, rhyolite

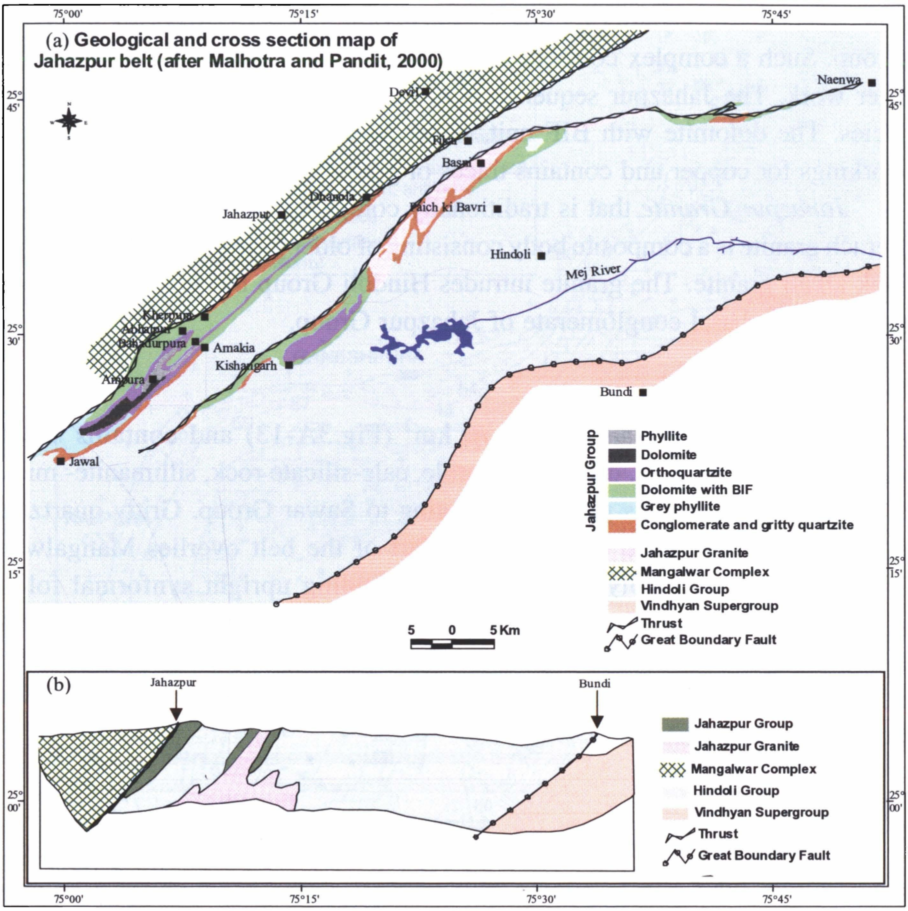

75°00'
75°15'
75°30'
75°45'
(a) Geological and cross section map of Jahazpur belt (after Malhotra and Pandit, 2000)
N
E
25° 45'
25° 30'
25° 15'
25° 00'
Devli
Naenwa
Basni
Dhanoda
Jahazpur
Paich ki Bavri
Hindoli
Mej River
Kherpura
Bahadurpura
Amakia
Kishangarh
Ampura
Jawal
Bundi
Jahazpur Group
Phyllite
Dolomite
Orthoquartzite
Dolomite with BIF
Grey phyllite
Conglomerate and gritty quartzite
Jahazpur Granite
Mangalwar Complex
Hindoli Group
Vindhyan Supergroup
Thrust
Great Boundary Fault
5 0 5 Km
(b)
Jahazpur
Bundi
Jahazpur Group
Jahazpur Granite
Mangalwar Complex
Hindoli Group
Vindhyan Supergroup
Thrust
Great Boundary Fault

**Fig.3A-12.** (**a**) Geological map and (**b**) Cross-section of Jahazpur belt (after Malhotra and Pandit, 2000).

and ignimbrite, quartz arenite, dolomite with pockets of talc, purple phyllite, carbonaceous phyllite and basic volcanics. The basal polymict conglomerate unconformably overlies Hindoli Group, and the associated gritty quartzite is cross-bedded. The eastern sub-belt has the same lithostratigraphy but for the lack of upper formations above the dolomite, and that the basal conglomerate and paleosol overlie Jahazpur granite. Jahazpur belt shows three phases of deformation, with the early isoclinal folds of two phases superposed by the last phase. The axial planar foliation of Hindoli Group is truncated by the isoclinally folded Jahazpur unconformity. This field relation suggests that the middle part of Aravalli Supergroup represented by Hindoli Group is overlain with an unconformity after folding, by the middle Aravalli marked by Jahazpur Group. Such a complex correlation will have to be satisfactorily resolved by later work. The Jahazpur sequence is metamorphosed mainly in greenschist facies. The dolomite with BIF unit, along with carbonaceous shale, has old workings for copper and contains traces of gold.

*Jahazpur Granite* that is traditionally compared with the ~2600 Ma old Berach granite is a composite body consisting of older grey granite and younger pink alkali granite. The granite intrudes Hindoli Group but non-conformably underlies the basal conglomerate of Jahazpur Group.

### *Sawar Belt*

This belt covers an area of 70 km$^2$ (Fig.3A-13) and contains basal conglomerate, quartzite, dolomitic marble, calc-silicate rock, sillimanite- mica schist and carbonaceous phyllite belonging to Sawar Group. Gritty quartzite and basal conglomerate in the eastern part of the belt overlies Mangalwar Complex unconformably. The early N-S trending upright synformal folds produced conical folds by plunge inversion. Pb-Pb model ages of galena suggest a source age of 2030 Ma, with later remobilisation of ores at 1735 Ma. Chalcopyrite-pyrrhotite-galena-sphalerite ores are localised in this belt in favourable structures.

### *Pur-Banera Belt*

A linear sedimentary belt comprising basal conglomerate, quartzite, garnetiferous mica schist, orthoamphibolite, BIF, calc-silicate rocks, dolomitic marble, chert and BIF (Banera Group) unconformably overlies Mangalwar Complex with structural discordance. Pur-Banera belt is a major syncline consisting of E-W trending early synclines superposed by N-S trending upright folds. The sequence is metamorphosed under amphibolite facies. BIF and carbonates host strata-bound zinc-lead-copper mineralisation.

### *Rajpura-Dariba Belt*

Dariba Group unconformably overlying Mangalwar Complex consists of basal conglomerate and quartzite, dolomitic marble, calc-silicate rock, garnet-kyanite-staurolite-chloritoid-graphite-mica schist, and ferruginous and manganiferous cherts. The Rajpura-Dariba belt is involved in three phases of folding and metamorphism of amphibolite facies. Zircon Pb-Pb dates suggest a range from ~2350 to 1800 Ma, encompassing the ages of the source and mobilisation of ores.Synsedimentary Pb-Zn-Cu mineralisation is prominent. Silver mineralisation in dolomite marble is reported from *Bharak belt* that is

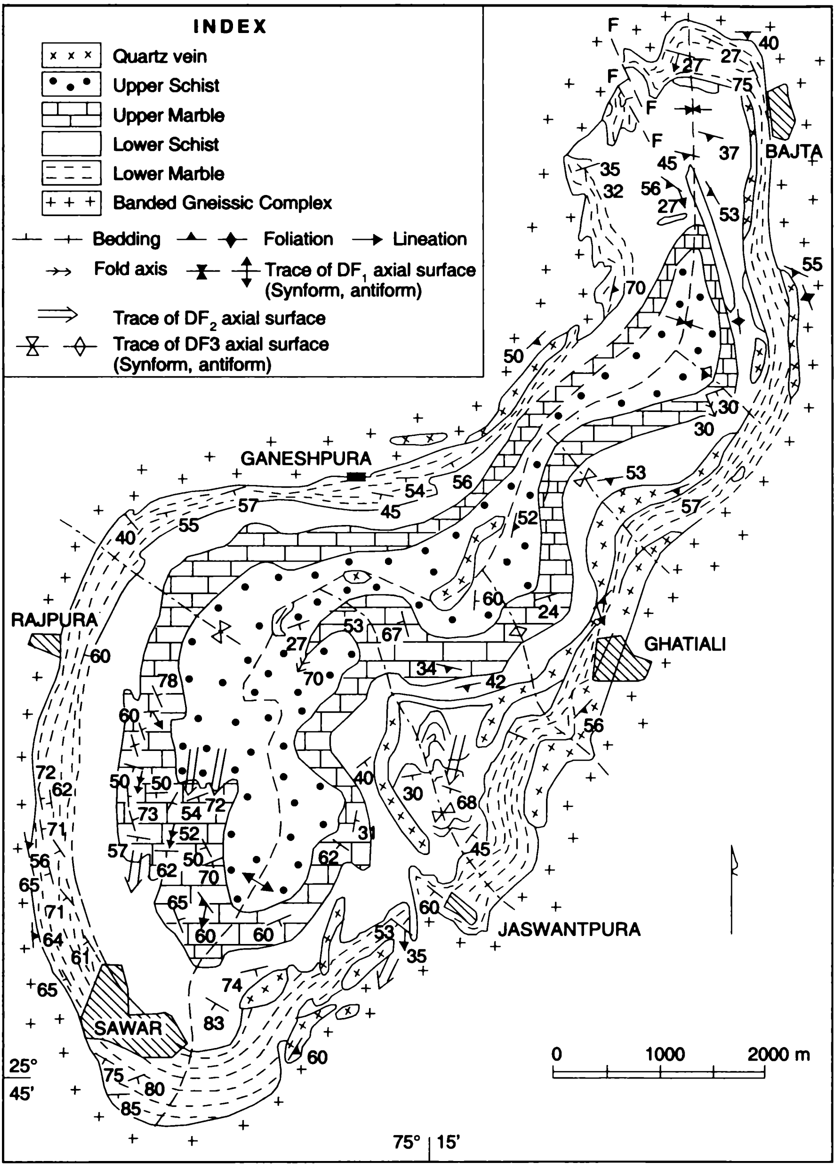

INDEX
Quartz vein
Upper Schist
Upper Marble
Lower Schist
Lower Marble
Banded Gneissic Complex
Bedding
Foliation
Lineation
Fold axis
Trace of DF$_1$ axial surface (Synform, antiform)
Trace of DF$_2$ axial surface
Trace of DF3 axial surface (Synform, antiform)
BAJTA
GANESHPURA
RAJPURA
GHATIALI
JASWANTPURA
SAWAR
F
N
25°
45'
75°
15'
0
1000
2000 m

Fig.3A-13. Geological map of Sawar belt (after Roy, 1988).

considered by some authors as a separate belt which contains in addition metabasic and acid volcanics.

*Rampura-Agucha Belt*

This belt, located close to Delwara Lineament at the contact of Mangalwar and Sandmata Complexes to the west of Sawar belt, hosts the largest Pb-Zn deposit in the country (Gandhi, 2003). Agucha Group consists of a metasedimentary sequence of garnet-biotite-sillimanite gneiss, graphitic biotite-sillimanite gneiss, basaltic and andesitic amphibolite and calc-silicate rock. Graphitic biotite-sillimanite gneiss is the main host for sulphide mineralisation. Mg-rich dravite (tourmaline), characteristic of massive sulphide deposits, is common in the mineralised zone. Three successive phases of deformation are encountered in the belt. The first phase produced NNE trending isoclinal, reclined folds that was followed by the second phase of tight isoclinal folds and the third phase of weak open folding. The metamorphism is of upper amphibolite facies marked by the presence of sillimanite and K-felspar with attendant migmatisation. Pb-isotopic model age of galena from this belt is around 1800 Ma. Ar-Ar ages of biotite, muscovite and hornblende showed a range from 800 Ma to 900 Ma that may indicate cooling and exhumation events.

### *Bhindar Belt*

The narrow Bhindar belt is described as the southern extension of either Rajpura-Dariba or Pur-Banera belt. Bhindar Formation consists of quartzite with local conglomerate, dolomitic marble, graphitic mica schist, metabasalt and amphibolite. Deformation and metamorphism of Bhindar belt are similar to that of Pur-Banera belt.

## PROTEROZOIC ARAVALLI-DELHI OROGEN

The Proterozoic Aravalli-Delhi orogen trending NE-SW stitches together the Mewar and Marwar cratons and consists of Palaeoproterozoic Aravalli fold belt and Mesoproterozoic Delhi fold belt. The orogen is well known for its rich base metal resources. It is bounded in the east by the Kaliguman Lineament in the middle, by the folded unconformity between Mangalwar Complex and Delhi Supergroup in the north, and a similar unconformity between Mewar Gneiss and Aravalli Supergroup in the south. Kaliguman Lineament separates Sandmata Complex from Delhi fold belt in the north and marks the Aravalli-Delhi contact in the south. In the west, the orogen is bounded by the Phulad Lineament situated between Delhi fold belt and Marwar craton. Both the fold belts consist respectively of shelf facies in the east and deep-water facies in the west, with a westward polarity. The deep-water facies in both have ultramafic-mafic belts that are interpreted as ophiolites in a plate tectonic framework. The tectonic boundaries of the orogen expose slices of deep-seated charnockites, viz. Sandmata granulites close to Kaliguman Lineament, and Pilwa-Chinwali granulites in the north near Phulad Lineament. The orogen links up with CITZ of Satpura mobile belt in the east beneath the cover of Deccan Trap (Fig.3BK-2).

## Palaeoproterozoic Aravalli Fold Belt

Palaeoproterozoic Aravalli fold belt (2200-1800 Ma) (Fig.3A-14) is a prominent and well-studied litho-tectonic unit of the Aravalli craton. The fold belt displays conspicuous Proterozoic characteristics like the presence of phosphatic stromatolites, dolomites in preference to calcic limestones, carbon and oxygen isotopic signatures of sediments, prominent lead-zinc mineralisation, local oligomictic quartz-pebble conglomerate (QPC), red beds

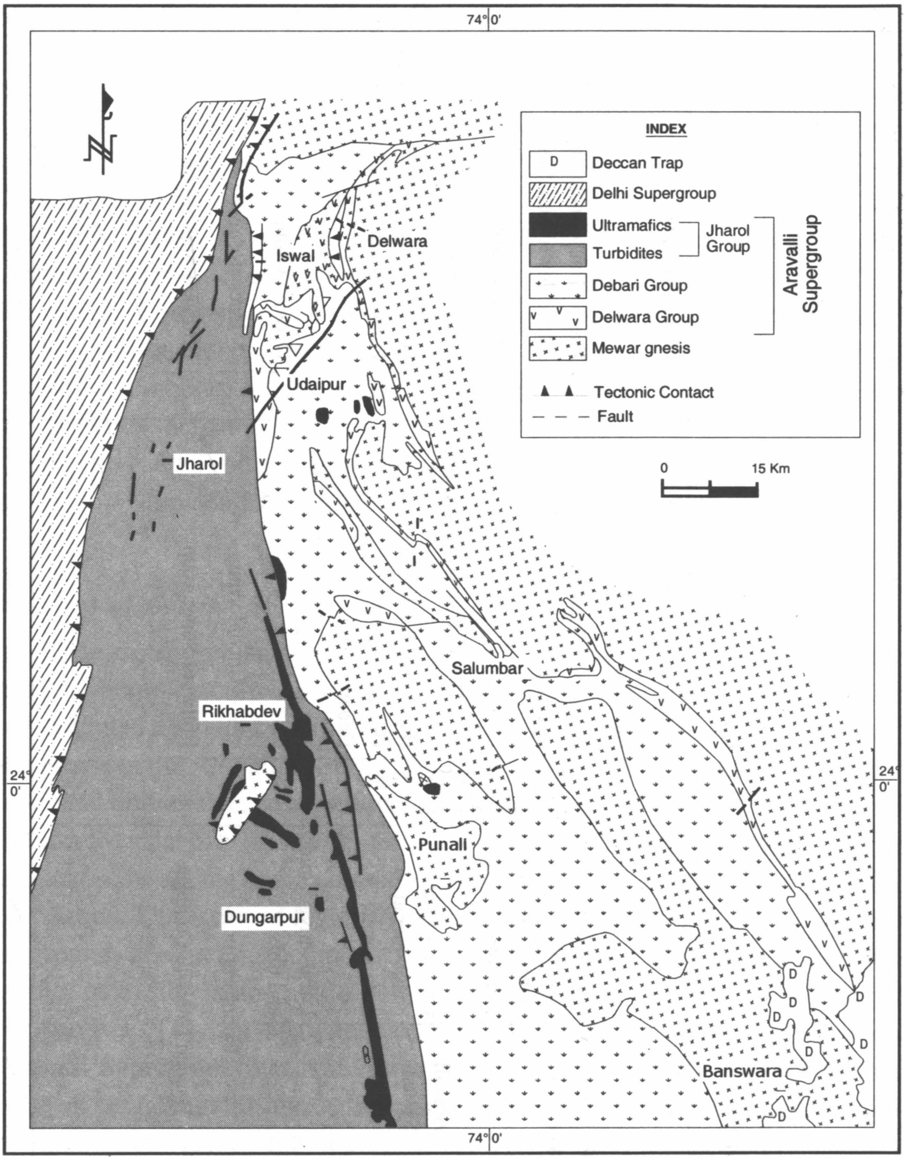

74° 0'
N
INDEX
D Deccan Trap
Delhi Supergroup
Ultramafics
Turbidites
Jharol Group
Debari Group
Delwara Group
Aravalli Supergroup
Mewar gnesis
Tectonic Contact
Fault
0
15 Km
Iswal
Delwara
Udaipur
Jharol
Salumbar
Rikhabdev
Punali
Dungarpur
Banswara
D
24° 0'
24° 0'
74° 0'

**Fig.3A-14.** Geological map of Aravalli fold belt (after Gupta et al. 1997).

**Table 3A-1.** Stratigraphic schemes of Aravalli Supergroup

| Heron (1953) | | Gupta et al. (1997) | | Sinha-Roy et al. (1998) | | Roy and Jakhar (2002) | | |
|---|---|---|---|---|---|---|---|---|
| | | ARAVALLI SUPERGROUP (2000-2500 MA) | Champaner Group | ARAVALLI SUPERGROUP | Darwal Granite | ARAVALLI GROUP | UPPER | Serpentinite |
| | | | Lunavada Group | | | | | Lakhavali Phyllite |
| Granite, basic and ultrabasic rocks | Impure limestone, quartzite, phyllite, biotite schist and composite gneiss | | Granites, Rikhabdev ultramafic suite | | Jharol Group (including Rikhabdev ultramafics) | | | Kabita Dolomite<br>Debari Formation |
| | | | | | Unconformity | | | |
| Aravalli System | Quartzite, grit, conglomerate & soda syenite | | Jharol/Dovda/Nathdwara Groups | | Leucogranite | | MIDDLE | Tidi Formation |
| | | | Bari Lake/ Kankroli Groups | | Debari Group (including Jahazpur, Pur-Banera, Rajpura-Dariba etc. belts) | | | Bowa Formation |
| | | | Udaipur Group | | | | | Mochia Formation |
| | | | Debari Group | | | | | Udaipur Formation |
| | Local amygdaloids and tuffs | | | | Delwara Group | | LOWER | Jhamarkotra Formation<br>Delwara Formation |
| - - - -Unconformity - - - | | | - - - - -Unconformity - - - - | | --- Unconformity - - - | | | |
| Banded Gneissic Complex | | | Bhilwara Supergroup | | Bhilwara Supergroup | | | |
| | | | | | | | | - - -Unconformity - - - |
| | | | | | | | | Mewar Gneiss |

and manganese formations. Orthoquartzite-carbonate facies is very conspicuous throughout the succession.

### *Extent*

The areal extent of the Aravalli fold belt is a matter of controversy. The controversy has arisen because the basement-cover unconformity between the Aravalli Supergroup and Mewar Gneiss is clearly exposed to the south of Nathdwara, whereas to the north of Nathdwara, the schistose rocks are highly metamorphosed and migmatised, obliterating the basement-cover relationship. Geological Survey of India (Gupta et al. 1997) ended the fold belt in a few fold closures near Amet, to the south of Sandmata granulite belt. Sinha-Roy et al. (1998) closed the Aravalli fold belt further south at the E-W trending Nathdwara fault extending into Banas Lineament. They described the shape of the belt as an inverted V with the apex near Nathdwara and flaring southwards. Roy and Jakhar (2002), in conformity with the views of Heron (1953) and Naha and Mohanty (1988), closed the fold belt near Amet. They also included in the Aravalli fold belt the large terrain to the east of Delwara Lineament (i.e., Mangalwar Complex and Hindoli Group). Despite this controversy, in this book, the northern boundary of Aravalli fold belt is placed near Amet, to the south of Sandmata Complex because of lithological and structural continuity despite the complex deformation and increase in metamorphic grade across the Nathdwara fault. The southern boundary of the Aravalli fold belt extending up to the Son-Narmada Lineament (CITZ) is not, however, in dispute.

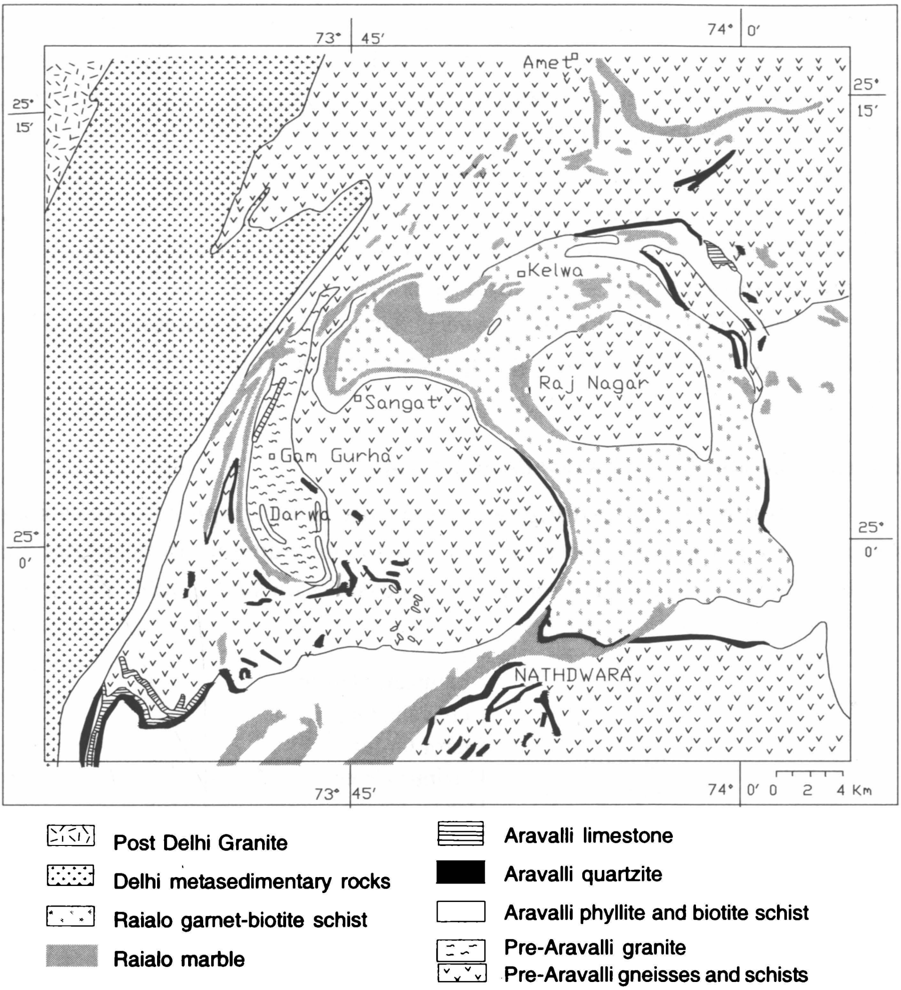
### *Problems of Correlation*

The main problems of stratigraphy of Aravalli fold belt are due to the gneissic complex constituting the basement for the most part, whereas it is reconstituted by partial melting in other areas. Various 'internal' and 'external' granitoids in the Aravalli fold belt are interpreted by different authors as either basement or intrusive, complicating the stratigraphy around these bodies. There are also frequent overlaps of litho-units, local unconformities marked by laterite and arkose or pebble bed, and repetition by folding, which cause problems for correlation. The assumed regional younging of beds to the west that is disputed on grounds of structural complications, and repetition of beds interpreted either as due to cyclic sedimentation or folding has led to different stratigraphic perspectives. This has led to the proposals of various stratigraphic schemes for Aravalli Supergroup that is divided into various groups and formations, but there is disagreement about the nomenclature, order of superposition and correlation of various lithological units. The various stratigraphic schemes proposed by different authors are given in Table 3A-1.

Heron (1953) described the rocks of Aravalli "System" resting on BGC with a profound unconformity. He listed several isolated belts and enclaves in BGC containing carbonate-pelite association as extensions of Raialo "Series" (e.g., Rajpura-Dariba, Pur-Banera). The controversial status of Raialo "Series" is recently resolved by placing it within the Delhi Supergroup and omitting it altogether from the Aravalli sequence. Gupta et al. (1997) divided the shelf facies extending from the south near Debari to the north near Amet into many groups, viz. Debari, Udaipur, Bari Lake, Kankroli, Jharol, Nathdwara and Dovda Groups. They described the deep-sea facies as Jharol Group occurring to the west. In the south, where the sequence fans out, the upper units that differ from the rest of the Aravalli succession have been named by them as Lunavada and Champaner Groups. The Aravalli succession approximately to the north of Amet, considered by Heron (1953) as Aravalli, was classified by Gupta et al. (1997) as pre-Aravalli and designated as Mangalwar Complex and Sandmata Complex. Sinha-Roy et al. (1998) broadly adopted the scheme of Gupta et al. (1997) with modifications, especially by introducing granitic activity between different groups. Another significant difference is that they divided the isolated and mineralised chemical sedimentary belts such as Rajpura-Dariba, Pur-Banera etc. as Aravalli-equivalent belts resting unconformably on the pre-Aravalli sequence of Mangalwar Complex. Roy and Jakhar (2002) divided Aravalli Supergroup into Lower, Middle and Upper Groups, which is not in conformity with stratigraphic codes and therefore will have to be treated as informal units. They correlated the high-grade rocks occurring to the north of Nathdwara and south of Sandmata Complex within the Aravalli Supergroup, and negated their pre-Aravalli status because of lithological continuity and structural unity.

### *Stratigraphic Status of High-grade Supracrustals within Aravalli Belt*

There is a raging controversy as to whether the supracrustal rocks occurring in the hammerhead and hook syncline area (Fig.3A-15) between Nathdwara and Amet belong to Aravalli or pre-Aravalli sequence. Those who believe in their correlation with Aravalli Supergroup (Heron, 1953; Naha and Mohanty, 1988; Gupta et al 1997; Roy and Jakhar, 2002) base their conclusion on the lithological and structural continuity, but with significant differences in metamorphism, basement reworking and migmatisation, noticed to the north of Nathdwara fault. This is evident from the inclusion of high-grade rocks of Kankroli and Dovda Groups (essentially amphibolites and paragneisses) within Aravalli Supergroup by Gupta et al. (1997), whereas Sinha-Roy et al. (1998) include them under the pre-Aravalli greenstone-type sequences (Tanwan and Sawadri Groups) of Mangalwar Complex. Similarly, in the Jagpura and Banaswara areas far to the south, some areas of Jharol Group are metamorphosed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Delhi metasedimentary rocks
Raialo garnet-biotite schist
Raialo marble
Aravalli limestone
Aravalli quartzite
Aravalli phyllite and biotite schist
Pre-Aravalli granite
Pre-Aravalli gneisses and schists

**Fig.3A-15.** Geological map of 'hammerhead and hook syncline' between Nathdwara and Amet (after Heron, 1953). The index is in accordance with Heron's (1953) classification.

to banded gneisses, but are still correlated with Aravalli Supergroup (Gupta et al. 1997; Sinha-Roy et al. 1998), rather than with pre-Aravalli sequence. Gupta and Mukherjee (1938) correlated these Jagpura-Banaswara rocks with BGC, and this view was adopted by Roy and Jakhar (2002). It is therefore clear that areas of high-grade schistose rocks of Aravalli fold belt have been mistakenly assigned pre-Aravalli status by some authors, despite their stratigraphic and structural continuity with Aravalli Supergroup.

The metamorphic transition of the same lithology from low grade to high grade in the area across the Nathdwara fault shows that the contact does not mark a stratigraphic break. The stratigraphic similarity is also corroborated by the dating of intrusive granites. For example, the 'hammerhead syncline' in the north of Nathdwara fault contains younger granite intrusions related to Aravalli orogeny. One of them, the Darwal Granite is a pear-shaped intrusion into the Aravalli sediments and volcanics. It is normal granite containing K-felspar, quartz and biotite. Rb-Sr isochron age of 1900±80 Ma of the granite indicates its syntectonic emplacement during Aravalli orogeny. Similarly, the Amet (Anjana) granite, which varies from augen gneiss to porphyritic granite, intrudes banded gneisses and is dated at 1641±4 Ma by single zircon ion probe, although Rb-Sr isochron ages are 1870±200 Ma. The medium to high-grade supracrustal rocks between Nathdwara and Amet are therefore correlated with Aravalli Supergroup in this book, following Gupta et al. (1997).

## Present Classification of Aravalli Supergroup

The following lithostratigraphic classification adopted from various schemes is derived from the type area of Aravalli Supergroup near Udaipur and is in conformity with the foregoing discussions on stratigraphic problems.

| | |
|---|---|
| Aravalli Supergroup | Champaner Group |
| | Lunavada Group |
| | Jharol Group |
| | Udaipur Group |
| | Debari Group |
| | Delwara Group |
| | - - -Unconformity- - - |
| | Sandmata Complex |
| | Mangalwar / Sandmata Complex |
| | Mewar Gneiss with enclaves of Jagat Group |

## Description of Lithostratigraphy

The lithological ensemble of Aravalli fold belt is called the Aravalli Supergroup, which has two distinct facies associations (Fig.3A-16). The lower clastic and chemical sediments with basic volcanics belong to the shelf association, whereas the upper greywacke-phyllite suite forms the deep-sea facies. The two facies associations have an ultramafic-mafic suite at their contact zone, which has been interpreted as marking an ophiolite suture. In the present classification, the shelf facies includes the quartzite-volcanics-carbonate sequence of Delwara Group, polymict conglomerate-quartzite-carbonate-pelite sequence of Debari Group, and proximal greywacke-pelite-carbonate sequence of Udaipur Group. The Debari Group of other authors has been divided here into Debari and Udaipur Groups in order to distinguish the two different

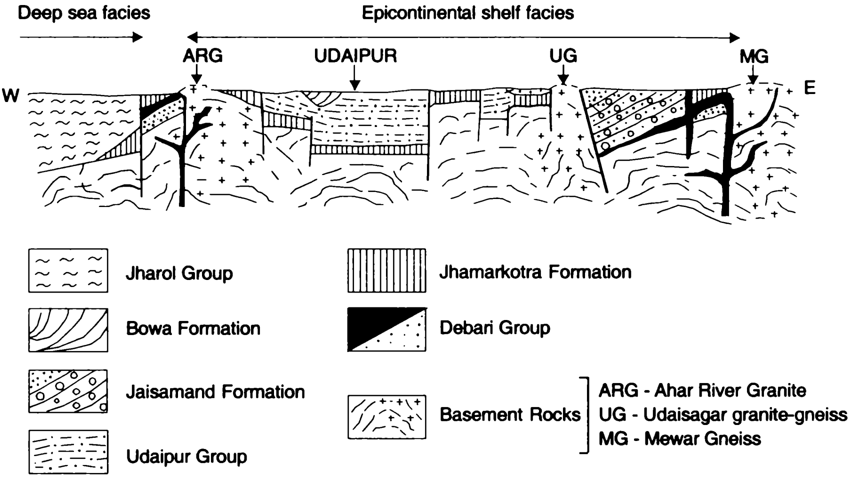
Deep sea facies
Epicontinental shelf facies
ARG
UDAIPUR
UG
MG
W
E
Jharol Group
Bowa Formation
Jaisamand Formation
Udaipur Group
Jhamarkotra Formation
Debari Group
Basement Rocks
ARG - Ahar River Granite
UG - Udaisagar granite-gneiss
MG - Mewar Gneiss

**Fig.3A-16.** Schematic section of Aravalli stratigraphy near Udaipur (after Roy and Jakhar, 2002, p.84).

lithological associations having diverse environmental connotations, with also a hiatus in sedimentation. The deep-sea facies is marked by the distal greywacke-pelite suite of Jharol Group. The coarse quartzite-siltstone-mangan phyllite-dolomite suite of Lunavada and Champaner Groups is regarded as post-orogenic, molasse-like sediments. The various stratigraphic groups of Aravalli Supergroup are described below:

### Delwara Group

Delwara group is best exposed between Nathdwara and Pipalkhunt for over 300 km with an average width of 500m. Spectacular angular unconformity between the Mewar Gneiss and Aravalli Supergroup is exposed from Nathdwara to Salumbar, marking one of the ancient Proterozoic strandlines (Fig.3A-17). Near Delwara, two parallel belts of basal succession are exposed, separated by a sliver of basement gneiss. The basement-cover interface is marked by a significant occurrence of discontinuous pockets of paleosol. The paleosol is represented by pockets of white mica (2M-type sericite) having sharp boundary with the overlying quartzite. The paleosol locally contains kyanite and fuchsite. Laterally, it grades into quartzose rocks containing chloritoid, tourmaline, biotite and magnetite. A thin layer of meta-arkose or 'granite wash' locally underlies the white mica pockets. Geochemical studies show enrichment of Rb, Zr, Ti and Cr and depletion of Sr in paleosol, which is a characteristic feature of chemical weathering of a granite source. LREE enrichment reflects abundance of zircon and rutile. These features overrule the possibility of white mica pockets as products of shearing or hydrothermal alteration.

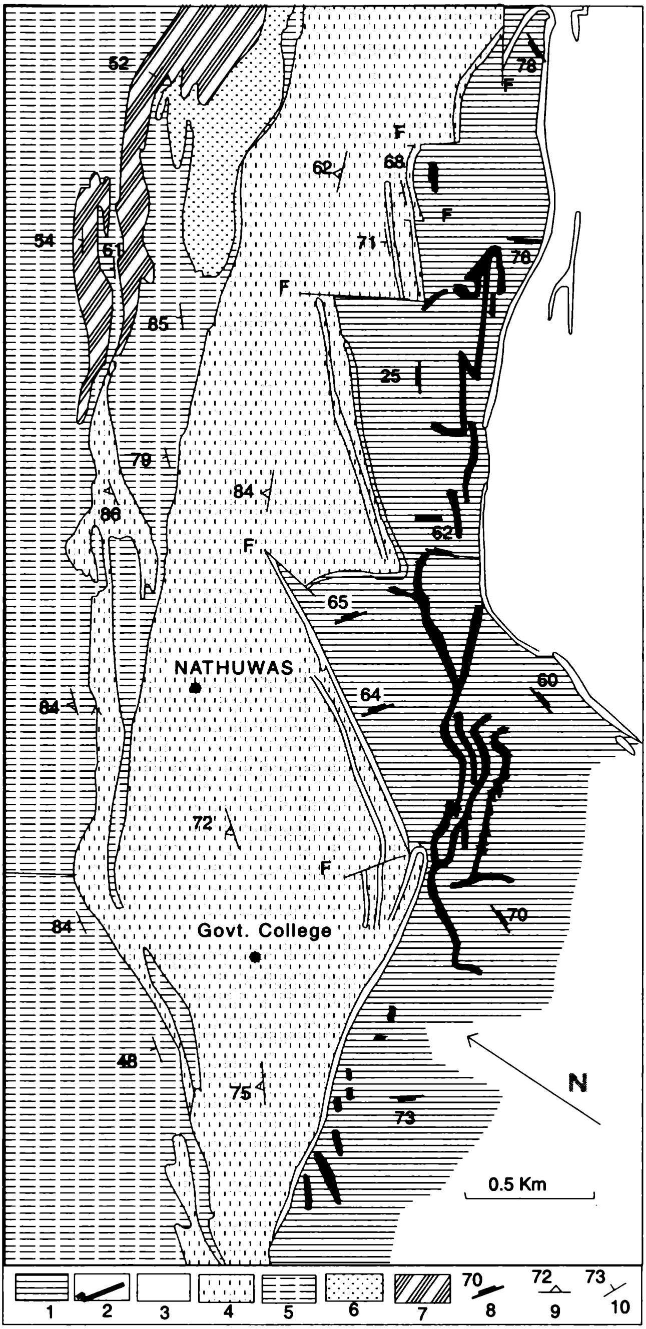
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**Fig.3A-17.** Unconformity between Mewar Gneiss and Aravalli Supergroup near Nathuwas, SE of Nathadwara (after Roy et al. 1988a). 1 - Mewar Gneiss; 2 - Jagat Group quartzite; 3 - Basal Aravalli quartzite with white mica deposits at its base; 4 - Basal Aravalli metavolcanics; 5 - Dolomitic marble; 6 - Orthoquartzite; 7 - Phyllite and mica schist with thin bands of dolomite; 8 - Dip of gneissic foliation in BGC; 9 - Dip of schistosity in the cover rocks; 10 - Dip of bedding in cover metasediments. F - Fault.

Delwara Group starts with a pebbly orthoquartzite (QPC). Arkosic quartzite is rare. The quartzite band is offset along its strike by several transverse faults (Fig.3A-17). A thin veneer of metavolcanics intervenes rarely between the gneiss and quartzite. The quartzite is overlain by a major volcanic unit called informally as Delwara volcanics consisting of amygdular basic flows intercalated with pyroclastic and epiclastic deposits, including volcanic conglomerates. Seven flows have been delineated at Delwara. Pahoehoe flows are rare. The lower flows are locally porphyritic with phenocrysts of hornblende and plagioclase. The upper flows are subophitic to granular. Metabasalts are massive and schistose and consist of actinolite, chlorite, albite-oligoclase, epidote and calcite with rare hornblende and biotite.

Delwara volcanics are mainly normal and Fe-rich tholeiites (<10%MgO), with subordinate high Mg basalts (>10%MgO) and komatiites in basal sections. Most of the volcanics are LILE and LREE enriched continental basalts. The basal Mg-rich volcanics may have been produced by variable degree of partial melting of enriched mantle sources. Delwara volcanics are generated by continental rifting or through plumes rising from the base of the crust.

The volcanics are interbedded with thin 'inter-trappean' beds of dolomite, quartzite and BIF. Delwara volcanics are exposed around Ahar River granite near Udaipur, along the northern margins of Sarara inlier, and around Bagdunda dome. There is a dispute about the status of Bari Lake volcanics, which are believed by some authors to represent the second, younger phase of volcanism. Bari Lake volcanics are interbedded with arkose, quartzite, carbonate and a quartz pebble conglomerate, and are similar to Delwara volcanics.

## Debari Group

Delwara volcanics are overlain by Debari Group consisting of a thick horizon of petromict conglomerate (Fig.3A-18a), pebbly arkose and felspathic quartzite. The conglomerate extends from Kailashpuri to Salumbar and has maximum thickness of 2500 m near Debari. Closely associated with the polymict conglomerate are bands of phyllite and dolomite. Debari Group corresponds to the Debari Formation of Sinha-Roy et al. (1998) and Jaisamand Formation/Group of Gupta et al. (1997) and Shekhawat et al. (2001). Roy and Jakhar (2002) included it under the 'Upper Aravalli Group' overlying the Udaipur Group in a stratigraphically higher position.

Debari polymict conglomerate consists of clasts of granite, gneiss, fuchsite quartzite and mica schist (all derived from the basement rocks of Mewar Gneiss) set in an arkosic matrix. Cross-bedded arkoses and felspathic quartzites are seen near Jaisamand. Similar conglomerate occurs around the Sarara and Mando inliers where they are called by local names. The conglomerate is overlain by

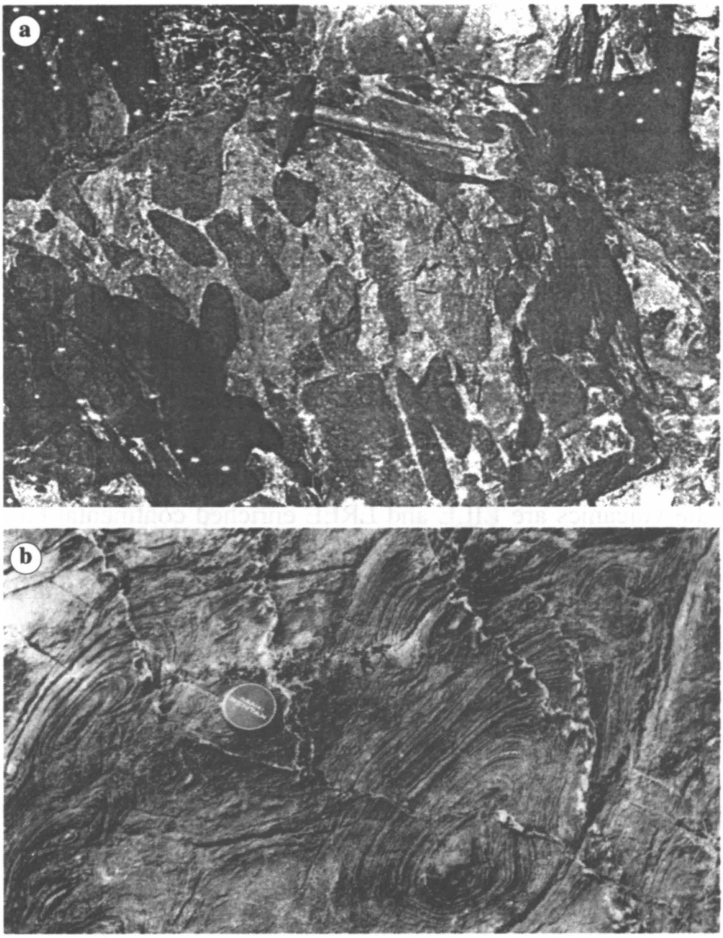

**Fig.3A-18.** (**a**) Debari conglomerate near Kailashpuri (Sinha-Roy et al. 1998). (**b**) Stromatolitic dolomite, Jhamarkotra (Roy and Jakhar, 2002, p.93).

a carbonate-pelite succession with a gradational contact. The overlying succession is called by some authors as Berwas and Jhamarkotra Formations. The basal carbonate unit, when it overlies the basement gneiss at Jhamarkotra, becomes a carbonate-mixtite unit similar to the Debari conglomerate. At other places, arkose and quartzite with pebble beds underlie the carbonate rocks. Berwas Formation consists of calcareous quartzite, carbonaceous phyllite, dolomite, ferruginous chert, mangan phyllite and quartzite. Jhamarkotra Formation contains, besides similar rocks, a variety of carbonate rocks. Grey dolomite is most widely developed unit that includes stromatolitic phosphorite and phosphatic dolomite. Collophane is the chief phosphatic mineral in phosphorite. Deposition of phosphorite is attributed to phosphate secreting algae in tidal flats, shelves and shoals. The other varieties of dolomite are ferruginous, carbonaceous, manganiferous and clayey, along with silcrete and ferricrete that form local unconformities. Three distinct stromatolitic assemblages are noticed viz., *Collenia columnaris, Collenia baicalica, Minjaria calccolata* as well as oncolites (Fig.3A-18b). Carbon phyllite overlies the dolomite at Umra and hosts minor Cu-U mineralisation.

## Udaipur Group

Thick accumulations of flysch-like, proximal greywacke-phyllite intercalated with chemogenic and biogenic rocks constitute the Udaipur Group. The intercalations are essentially ferruginous dolomitic chert, phosphatic algal dolomite and carbonaceous to manganiferous phyllite. These rocks are included in Lakhawali Phyllite and Kabita Dolomite of Upper Aravalli Group by Roy and Jakhar (2002).

An illustrative geological section of greywacke-phyllite association occurs between Udaipur and Jaisamand. Graded bedded greywacke and laminated phyllite occur as alternations (Fig.3A-19a, b). Current ripple lamination and load casts are common in this rhythmic unit. Isolated lenses of pebbly and bouldery conglomerate with a phyllitic matrix occur within the greywacke-phyllite sequence. Pebbles are mostly quartzite, vein quartz, carbonates and granitic rocks of the basement. Four different facies associations of greywacke are noticed viz., (i) fine to medium grained quartzofelspathic greywacke, (ii) a combination of felspathic, quartzofelspathic greywacke and conglomerate, (iii) silty arenite, siltstone rhythmite and (iv) lithic greywacke. The greywackes show LREE enrichment and flat HREE with no Eu anomaly. REE patterns are similar to those of basement TTG gneisses suggesting their possible inheritance. In the southern extensions near Banswara, the greywacke suite together with its intercalations is metamorphosed to higher grade. The greywacke-phyllite association has been divided into several formations along the length of the Aravalli fold belt by different authors.

The greywacke-phyllite suite is overlain by a wide variety of dolomites associated with carbonaceous phyllite and quartzite called Mochia or Zawar Formation. Massive, arenaceous and phyllitic dolomites are the common varieties. The dolomite shows typical elephant skin weathering. Massive dolomite of Mochia/Zawar Formation hosts important Pb-Zn-Ag mineralisation and is exploited at Zawar mines. Conglomerate and arkose interbeds are also found within the sequence. The Mochia/Zawar Formation is overlain by phyllites and quartzose phyllites in which sedimentary structures are well preserved (Bowa Formation). Dolomitisation in the Zawar Formation probably occurred in a tidal flat environment and the overlying phyllite-quartzite sequence (Machhla Magra and Tidi Formations) deposited in a fluvial environment (Roy and Jakhar, 2002).

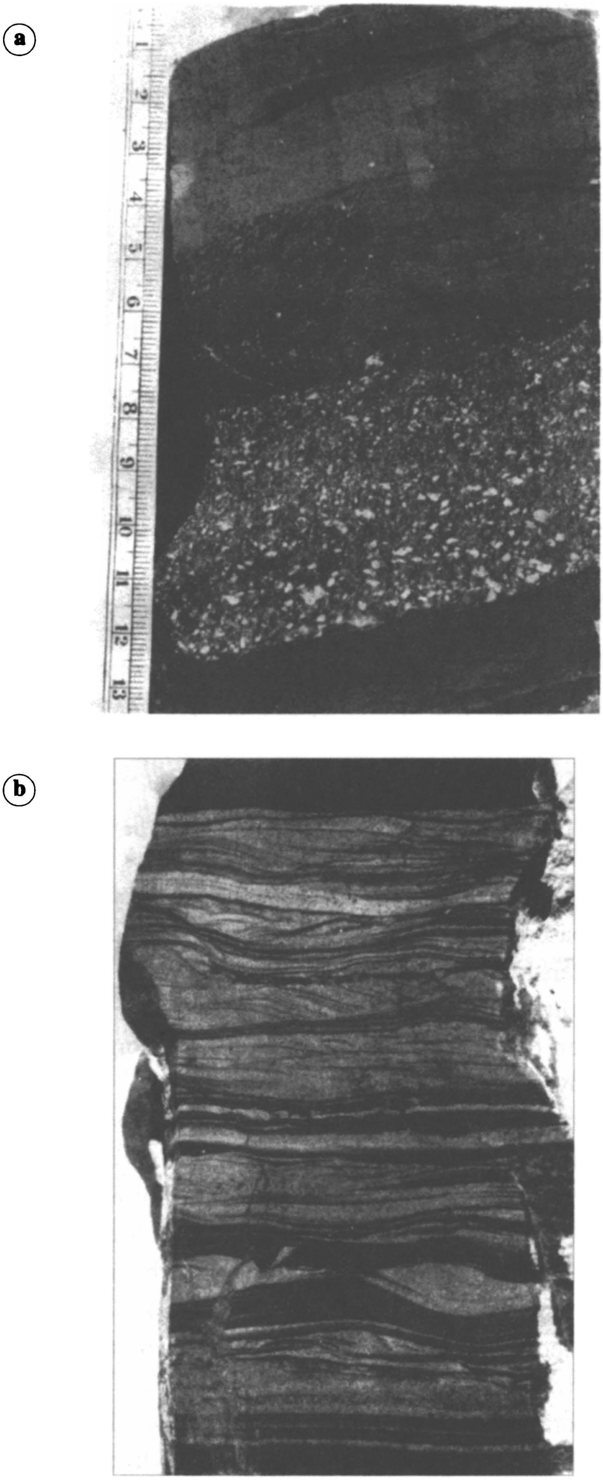
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**Fig.3A-19.** (**a**) Graded bedded greywacke and (**b**) Laminated beds of greywacke sequence (Photo: B.L Sharma from Roy and Jakhar, 2002, p.97).

### Jharol Group

Deep-sea facies of Aravalli Supergroup is manifested as a westward thickening sequence of carbonate-free pelites and arenites, which are interpreted as distal turbidites. A linear band of conglomerate marks the base of Jharol Group. Jharol group fans out to the south from Nathdwara for a distance of 200 km with a width of 40 km. Arenites of this group represent proximal land source and the lack of carbonates indicates deposition below the carbonate compensation depth.

### Rikhabdev Ultramafics

The shelf facies-deep sea facies interface is marked by the Rikhabdev (Rakhabdev or Rishabhdev) Lineament occupied by a discontinuous line of ultramafic rocks (Fig.3A-14). These are essentially serpentinites and talc-carbonate rocks that are interpreted as dismembered ophiolites marking a major suture zone in the Aravalli fold belt. These may represent ultramafic flows at some places and intrusive bodies at the other. Ophiolite stratigraphy is not clear and ophiolitic chemical signatures are not evident. There is therefore an alternate view that these may not represent ophiolites, but could be rift-related ultramafic intrusions.

### Lunavada Group

Lunavada Group occupies a polygonal area in the south of the Aravalli orogen. Structural discordance with Debari, Udaipur and Jharol Groups, absence of certain Aravalli deformational phases, abundance of sedimentary structures, presence of carbonates in contrast to their absence in Jharol Group and coarseness of lithology suggest that Lunavada Group is probably a younger unit resembling molasse sedimentation. The bulk of the group consists of greywacke-phyllite with associated quartz arenites. Minor bands of massive dolomite, phosphatic and stromatolitic dolomite, manganiferous phyllite and polymict conglomerate are also present. The extension of Rikhabdev ultramafics into the middle of this group suggests the alternate possibility that Lunavada Group may include components of Debari (shelf) and Jharol (deep sea) Groups. Since there are many such possibilities, the stratigraphic status of Lunavada Group is not clearly established.

### Champaner Group

Champaner Group occurs in a rectangular outcrop area surrounded by the intrusive Godhra Granite and by Deccan Trap. It consists of subgreywackes, siliceous phyllites, pelitic schists, quartzites and petromict conglomerates. Bands of dolomitic limestone and manganiferous phyllite near Shivrajpur are important from economic point of view. The sediments are metamorphosed to higher grades due to the thermal effect of Godhra Granite.

Champaner Group is folded into an anticlinorium plunging to the west. Open to tight isoclinal folds with E-W axial traces are the main deformational features. Champaner Group, together with the southern part of Lunavada Group, marks the deflection of structural trends towards E-W, from the NE-SW to N-S curved trends of the Aravalli sequence in the north, probably due to tectonic movements along the Son-Narmada Lineament.

The stratigraphic status of the Champaner Group is unclear because it is separated from the main fold belt by the younger cover and Godhra Granite. It is tentatively placed in the topmost part of the Aravalli Supergroup.

### *Structure*

Aravalli fold belt has been extensively studied structurally in several sectors (Roy and Jakhar, 2002). Broadly, the orogen has undergone three main phases of folding. The first generation ($F_1$) folds are tight to isoclinal and reclined folds with plunges in E and W, probably produced by simple shearing. These folds are responsible for the development of pervasive planar fabrics on mesoscopic scale. Second generation folds are of open to tight ($F_2$) with steep axial planes, and they control the map pattern. At some places, $F_1$ and $F_2$ folds are coaxial and at other places, they are orthogonal. Third generation folds ($F_3$) are open warps with subvertical axial planes that have trends athwart the pervasive schistosity. Open folds of fourth generation ($F_4$) are seen locally.

The 'hammerhead and hook synclines' between Nathdwara and Amet mark a departure from the normal fold pattern of the region (Fig.3A-15). A clockwise rotation of axial plane here is attributed to basement mobility. Imbrication of basal sequences at places may be due to listric faulting. Intense mylonitisation along with low plunge of lineation suggests strike-slip movement. At other places, vertical plunge of lineation may suggest oblique-slip movement. Dextral movement is reported from the Banas Lineament (Nathdwara Fault).

### *Metamorphism*

Middle amphibolite facies metamorphism together with quartzofelspathic veining, probably of medium pressure kyanite-sillimanite type, characterises the basement of Mewar Gneiss with enclaves of Jagat Group. The Aravalli sequence to the west shows mainly greenschist facies. Wherever there is mobility of the basement, the Aravalli metasediments attain higher metamorphic grade of amphibolite facies, as seen in the Nathdwara-Amet and Jagpura-Banswara areas.

### *Igneous Intrusions*

Several granitoid bodies occur within and at the margin of Aravalli fold belt. Some of them belonging to the basement are described under Mewar Gneiss. Others are regarded as intrusive by some and as basement by others. Such granites of controversial status are described below:

*Salumbar (Dudar) granite* is exposed intermittently for over 70 km with a width of 2-3 km. Tongues and veins of granite intrude the Aravalli metasediments near Salumbar. Similarly, *Fatehpur granite* intrudes the sediments of Debari Group. *Jaisamand granite* consists of grey gneissic granodiorite, tonalite and leucogranite forming a long narrow belt near Jaisamand (Dhebar) Lake. *Jhalara granite* is interpreted either as basement or as intrusive.

## Mesoproterozoic Delhi Fold Belt

The Mesoproterozoic Delhi fold belt (Main Delhi Synclinorium of Heron, 1953) is a linear belt about 450 km long with variable width. The fold belt exposes the rocks of Delhi Supergroup, named after Delhi, the capital of India. The belt spreads out in the north, becomes narrow in the middle and flares in the south. On plan view (Fig.3A-7), the belt appears like a large fan with a long handle that is narrow in the middle (Roy and Jakhar, 2002, p.155). The main Delhi fold belt in the middle has roughly an hourglass structure. The complex configuration of the belt has resulted in variable nature of contact with different stratigraphic units of the craton. In the north and south, the fold belt is lost under the Indo-Gangetic Alluvium with sparse outcrops jutting out from the plains. The fold belt is bound to the west by the Marwar craton along a tectonised and partly unconformable contact marked by the Phulad Lineament. In the broad portion of the belt towards northeast, the fold belt is in irregular unconformable contact with the pre-Delhi rocks of probably Mangalwar Complex. The eastern contact of the belt is marked by Kaliguman Lineament that is faulted against the Sandmata Complex in the north. In the south, Kaliguman Lineament forms a tectonised unconformity against the Aravalli fold belt.

The Delhi sediments are deposited in a few locally interlinked, but isolated basins (*see* Singh, 1988a) with the result the stratigraphic correlation is subjective, leading to several models now in vogue. Sinha-Roy et al. (1998) divided the orogen into two principal divisions of North Delhi Fold Belt (NDFB) and South Delhi Fold Belt (SDFB), principally based on contrasting ages of intrusive granites, namely, 1440-1660 Ma in NDFB and 730-960 Ma in SDFB. This division was disputed by Roy and Jakhar (2002) because they held that the rocks of NDFB are younger than that of SDFB, which is just the opposite of what the granite ages show. There is, however, a consensus on gross differences in geology between NDFB and SDFB. The dividing line separating them is called Bithur-Pisangan Line (or Rajgarh-Pisangan Line) near Ajmer that denotes an E-W fault or folded unconformity (Fig.3A-20). Delhi fold belt is divided into the following two belts for purposes of description.

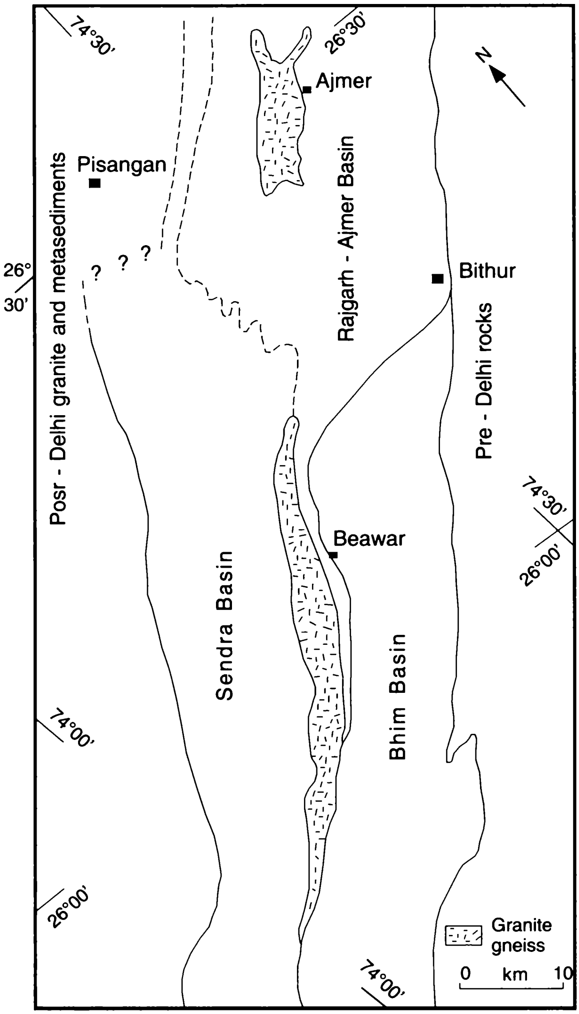
1. North Delhi Fold Belt includes the Khetri basin of the main Delhi belt. In the fanned out portion to the east of the main belt, NDFB contains loosely contiguous basins separated by faults, called (i) Bayana-Lalsot basin and (ii) Alwar basin
2. South Delhi Fold Belt is divided into two arms, viz. (i) the eastern Bhim basin, and (ii) the western Sendra basin, separated by the median Beawar gneiss forming the basement.

### *Previous Classifications*

Heron (1935) divided Delhi System of the entire Delhi belt into a lower arenaceous Alwar 'Series' and upper argillaceous Ajabgarh 'Series', although the division was meant mainly for NDFB. The Raialo 'Series' of quartzites and marbles was placed by him with a major unconformity between the Aravalli and Delhi 'Systems'. The Raialo outcrops in the Aravalli terrain of Bhilwara are now correlated with Aravalli Supergroup and Riaolo outcrops in the Delhi terrain are placed at the basal part of Delhi Supergroup (Gupta et al. 1997). Roy and Jakhar (2002) renamed the Raialo 'Series' of NDFB as Rayanhalla Group to remove the ambiguity in the definition and application of previous terminology.

Bayana-Lalsot and Alwar basins of the NDFB have similar stratigraphy. They contain approximately 70% clastic sediments, 10% carbonates and 20% volcanics. These basins unconformably overlie pre-Delhi (Mangalwar Complex?) supracrustals and granitic gneisses. Khetri basin of NDFB that occurs in the northern part of the main Delhi fold belt has a different stratigraphy from that of Bayana-Lalsot and Alwar basins. Khetri basin is also stratigraphically different from SDFB, and is separated from it by the alluvial cover and by the Bithur-Pisangan Line.

The classification of SDFB is more complex. Gupta et al (1980) followed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Posr - Delhi granite and metasediments
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Bithur
Pre - Delhi rocks
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Beawar
Sendra Basin
Bhim Basin
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26°00'
Granite gneiss
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**Fig.3A-20.** Division of NDFB and SDFB along Bithur-Pisangan line (after Roy and Jakhar, 2002).

Heron's (1953) classification for SDFB by proposing the name of Gogunda Group for the eastern basin that corresponds to Alwar Group, and Kumbalgarh Group for the western basin that corresponds to Ajabgarh Group. They also described the Phulad Ophiolite from Kumbalgarh Group. Sen (1981) proposed radically that the belt consists of a few tectonic units that have disrupted the stratigraphy, and this view formed the basis for subsequent classifications. Different names are proposed by different authors for various tectono-stratigraphic units whose mutual relations are in dispute. Further, there are many linear bands and enclaves close to the eastern and western boundaries of SDFB, and their correlation with the Delhi or pre-Delhi sequence is also controversial.

In summary, it may be stated that the Delhi fold belt is a conglomeration of many basins formed by different processes and their basin fill represents different tectonic environments (Gupta and Bose, 2000). The diachronous development of different basins suggested by sparse isotopic ages, unconformities between sequences and differences in depositional environments is regarded by some workers as controversial, because of similarity of structural evolution of the fold belt as a whole. Various tectonic models are proposed by different authors to explain the complex evolution of the fold belt, but there is only a modicum of agreement. There is therefore a vital need to expand the database to understand the fold belt better.

## North Delhi Fold Belt

### *Bayana-Lalsot Basin*

This basin forming the eastern limit of Delhi fold belt is situated close to Bharatpur. An erosional unconformity marks the boundary between Delhi and pre-Delhi rocks in the basin (Fig.3A-21).

*Raialo Group:* Basal conglomerate of Raialo Group is well-sorted and texturally mature, suggesting beach environment. The conglomerates and pebbly quartzites are overlain by a sequence of basic volcanics with sedimentary interbeds, named as Jahaj-Govindpura volcanics, which have a spread over 100 sq. km and thickness of one km. About 18 pahoehoe and aa flows are delineated. An early quiescent phase of amygdular basalts and tuffs is followed by an explosive phase of agglomerate, volcanic breccia and welded tuff. A quiescent phase similar to the early phase follows the explosive phase. Geochemical studies indicate that the volcanics are essentially tholeiitic to alkaline basalts with high $K_2O$ that is characteristic of continental basalts. The volcanics are probably derived from enriched mantle, as they do not apparently indicate any significant crustal contamination.

*Alwar Group* consists of a conglomerate, orthoquartzite, felspathic quartzite and arkose, along with minor shale.

*Ajabgarh Group* overlies Alwar Group disconformably and contains carbonaceous phyllites in the lower part and ferruginous quartzites in the upper part.

*Structure:* An early monoclinal fold trending NW-SE is superposed by later folds of NE-SW trends. Large faults have locally disrupted the stratigraphy. The basin represents an asymmetric graben bounded by two

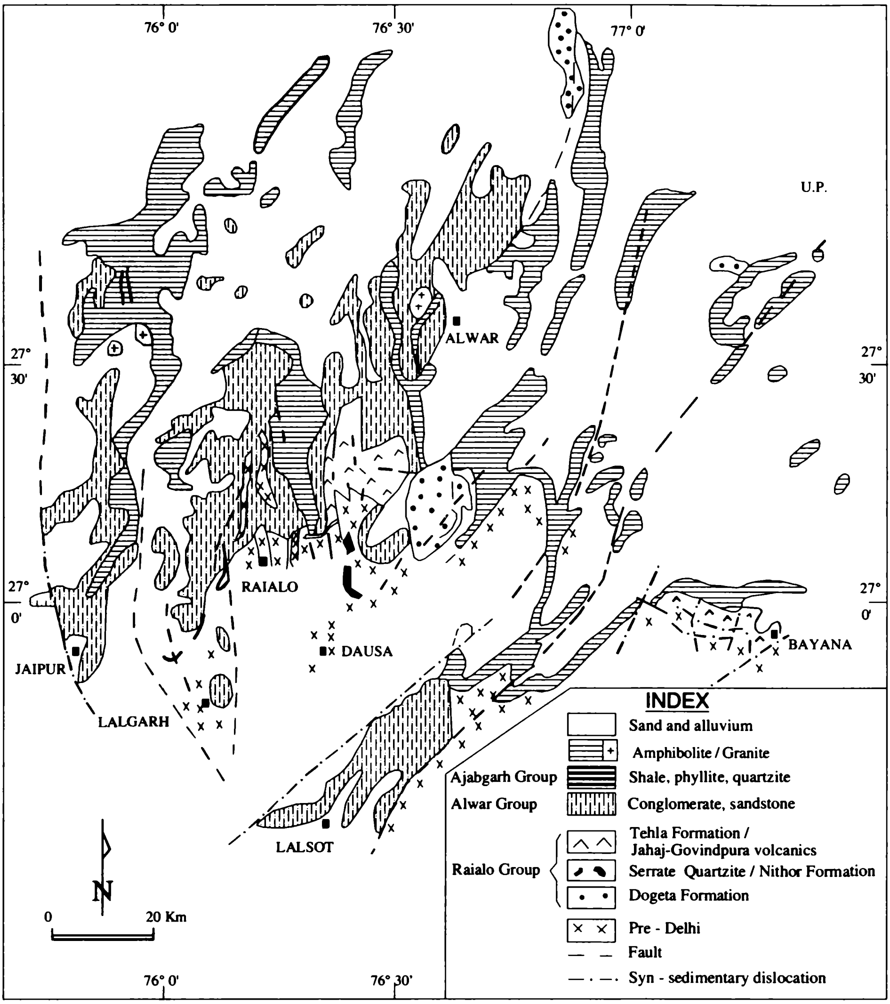

76° 0'
76° 30'
77° 0'
U.P.
ALWAR
27° 30'
27° 0'
RAIALO
DAUSA
BAYANA
JAIPUR
LALGARH
LALSOT
N
0
20 Km
76° 0'
76° 30'
INDEX
Sand and alluvium
Amphibolite / Granite
Ajabgarh Group
Shale, phyllite, quartzite
Alwar Group
Conglomerate, sandstone
Raialo Group
Tehla Formation / Jahaj-Govindpura volcanics
Serrate Quartzite / Nithor Formation
Dogeta Formation
Pre - Delhi
Fault
Syn - sedimentary dislocation

**Fig.3A-21.** Alwar and Bayana basins of NDFB (after Singh, 1988a; GSI, 2004).

sub-parallel faults. The provenance of the sediments is from the surrounding gneissic and supracrustal basement.

### *Alwar Basin*

This basin (Fig.3A-21) is located between the Bayana-Lalsot basin in the east and the Khetri basin of the main Delhi belt in the west. Alwar basin tapers to the south into Lalgarh graben. The boundaries of this belt with the adjacent basins are faulted.

*Raialo Group*: Raialo sedimentation started at the two independent depocentres of Dogeta and Makrana sub-basins. Carbonate sedimentation commenced first at Dogeta in a shallow basin under stable conditions. The poor clastic output in the sub-basin suggests subdued relief. This was followed by block fault and uplift (Dausa uplift) initiating rudaceous and arenaceous sedimentation in a transgressive beach environment. In the Makrana sub-basin, carbonate rocks, correlated with that of Dogeta sub-basin, were deposited first. The carbonates were marmorized to form the Makrana and Ras marbles that are excellent decorative stones. The carbonate sedimentation was followed by uplift accompanying faulting that caused the production of basic and acidic volcanics at Tehla, instead of the coarse clastics that followed carbonate sedimentation in Dogeta sub-basin.

*Alwar Group:* The overlying Alwar Group consists dominantly of quartzites and conglomerates deposited in braided stream, subtidal and tidal flat environments.

*Ajabgarh Group*: This sequence commences with carbonates and phosphorites, interlayered with basic volcanics. It is followed by alternations of quartzites, carbon phyllites, mica schists and marbles. The sedimentary environment is braided stream or alluvial fan followed by tidal flat to lagoon. Sedimentation is interrupted by intra-basinal volcanism related to faulting.

*Structure:* Alwar basin is involved in three-phase deformation with early isoclinal NNE trending folds, overprinted by folds with steep axial planes, and followed by the last phase of open folding.

*Intrusions in NDFB:* Amphibolites are dominant intrusions, followed by granites. *Bairat granite* consists of an early phase of foliated alkali granite and a younger phase of homophanous adamellite. *Ajitgarh granite* is a dominantly alkali granite with subordinate trondhjemite, intruded by two sets of pegmatite. Rb-Sr age of the granites is about 1650 Ma. *Barodia granite* is normal granite having a hypidiomorphic core and granophyric periphery. *Harsoria granite* consists of a cluster of bodies of normal granite.

### *Khetri Basin*

This 80 km long belt (Fig.3A-22) is important for its copper mineralisation and therefore is well known as Khetri copper belt. This belt has a complex history of structure, metamorphism, magmatism and mineralisation. The belt is subdivided into North Khetri belt (NKB) and South Khetri belt (SKB) separated by Kantli fault. NKB and SKB probably evolved independently with different basement-cover relationships viz. an unconformity in NKB and dextral

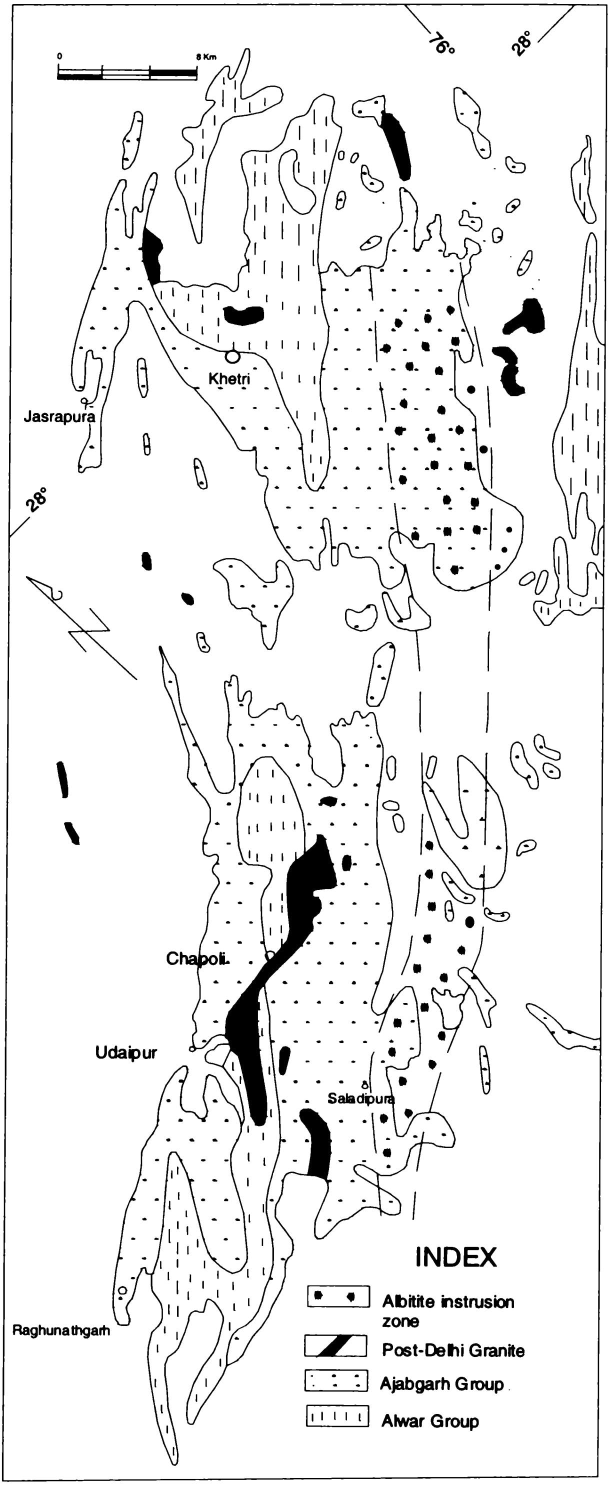

0
8 Km
76°
28°
28°
Khetri
Jasrapura
Chapoli
Udaipur
Saladipura
Raghunathgarh
INDEX
Albitite instrusion zone
Post-Delhi Granite
Ajabgarh Group
Alwar Group

**Fig.3A-22.** Khetri basin and Albitite Line (after Ray, 1990).

fault at the SKB contact. The two belts also differ significantly in their lithological association, especially in the presence of felsic volcanics in SKB.

### North Khetri Basin

The succession of NKB is called the Khetri Group that consists of ferruginous breccia, quartzite, amphibole-biotite quartzite, para-amphibolite, impure marble, garnet-chlorite schist, andalusite-biotite schist and metagreywacke. The unconformity with the basement is marked by ferruginous breccia and iron concentrations. The basement consists of tonalite gneiss containing enclaves of pelitic schist, quartzite, calc-silicate rock and marble. The structure of the belt is complex with a number of longitudinal anticlines and synclines, some of which show culminations and depressions. Metamorphism is of andalusite-sillimanite type in two episodes at 550 to 600±50° C and 3 to 5 kbar with the development of andalusite and cordierite. The basement is of polymetamorphic character.

*Granites:* Several granite bodies are present within NKB. These granites are named after the localities of Gotro, Seoli and Jasrapura. *Gotro granite* has intruded along the contact of basement and cover. *Seoli granite* has Rb-Sr age of ~1470 Ma. These dates reflect a major thermal event of ~1450 Ma in NKB. The Rb-Sr age of *Jasrapura granite* is ~1850 Ma that is similar to the age of *Anasagar gneiss* and both form basement to NKB.

### *South Khetri Basin*

The succession of SKB called the Shyamgarh Group consists from bottom to top of staurolite-garnet schist with pebbly quartzite; felsic volcanics and pyroclastics, carbon phyllite and chert; conglomeratic quartzite, garnet-mica schist, BIF; dolomite, calc-silicate rock, semipelitic schist and greywacke, graphitic schist; and micaceous quartzite. The sequence indicates that deep-water facies is overlain by the shallow water facies, in contrast to the reverse situation in NKB. The basement-cover interface is marked by the Chapoli fault. Two main phases of deformation are identified in SKB, viz. steeply inclined folds plunging towards NE to NNE, followed by coaxial refolding. Folding is accompanied by ductile shearing. The deformational phases of SKB and NKB are correlatable. Metamorphism of SKB is of kyanite-sillimanite type.

*Granites:* SKB is intruded by many granitic bodies. *Paniaras granite* is peraluminous, S-type granite that is partly migmatitic. *Chapoli granite* is oval-shaped granite that is homophanous at the core and gneissic at the periphery. It yields Rb-Sr isochron age of about 1340 Ma. *Udaipurwati granite* is a very long body that has an age of 1480 Ma and is similar in age to *Saladipura granite*. These granites suggest a major thermal event at 1450 Ma in SKB that is consistent with the isotopic ages from NKB. Rb-Sr mineral ages of various granites in NDFB are about 700-850 Ma that correspond to the ages of granitic activity in Marwar craton (Erinpura and Pali granites, 820-850 Ma).

### *Kishangarh Nepheline Syenite*

An interesting suite of alkaline rocks with nepheline syenite as the dominant component occurs around Kishangarh near Ajmer (Fig.3A-23) at the eastern contact of the North Delhi fold belt with gneisses of Sandmata Complex (?). The western contact of the body is marked by pre-Delhi supracrustals of quartzite, mica schist, marble and amphibolite, locally called the Kishangarh Group. The nepheline syenite is about 25 km long and 1-5 km wide and consists of 20-30% felspathoids and variable amounts of mafic minerals, besides the principal felspar minerals. Alkaline mafic rocks like felspathic ijolite as lenticular patches, theralite as xenoliths and comptonite as dykes occur locally within the alkali syenite. The intrusion is deformed into an elongate flattened dome refolded into hook shape. Complex folding and gneissic foliation at the margins suggest that it is a synkinematic intrusion associated with Delhi orogeny. Rb-Sr age of the body is ~1500 Ma.

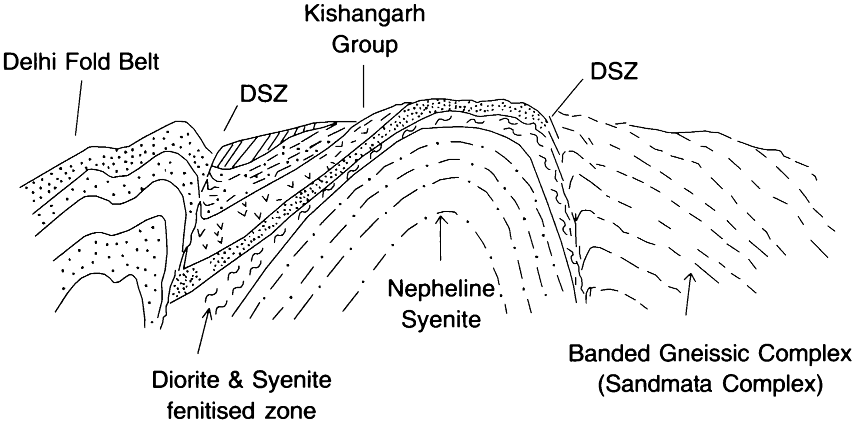

Kishangarh Group
Delhi Fold Belt
DSZ
DSZ
Nepheline Syenite
Banded Gneissic Complex (Sandmata Complex)
Diorite & Syenite fenitised zone

**Fig.3A-23.** Schematic cross-section of Kishangarh nepheline syenite intrusion (after Roy and Dutt, 1995). DSZ - Ductile shear zone

### *Newania Carbonatite*

A small lenticular body of carbonatite (2x0.5 km) trending NW-SE intrudes the Archaean Untala granite. It is described as a funnel-shaped body emplaced along an E-W low plunging fold axis. Petrographic types include rauhaugite, beforsite, rodbergite and sovite with lapilli carbonatite. Pyrochlore forms a valuable constituent of this carbonatite and its presence is reflected in LREE enrichment. A conspicuous zone of fenitisation occurs around the carbonatite. Pb-Pb isochron ages of different components of carbonatite are 2270 and 1550-1600 Ma. Rb-Sr age of 960 Ma probably indicates metamorphic impress.

### *Albitite*

A NE-SW trending zone of albitite intrusions (Fig.3A-22) extending for over 300 km cuts across the Delhi fold belt and the basement gneisses, and are associated with ultramafic rocks. These albitites are well known for uraninite-fluorite-magnetite-chalcopyrite-molybdenite mineralisation. Soda metasomatism is reported to be widespread in these albitites. Their linearity, alkalic affinity and mineralisation suggest deep, fracture-controlled emplacement in an intra-cratonic setting.

## South Delhi Fold Belt

South Delhi Fold Belt (SDFB), unlike the NDFB, exposes a continuous succession along NNE-SSW to NE-SW strike from Ajmer in Rajasthan to Himmatnagar in Gujarat (Fig.3A-24). It was earlier visualised in simple terms as made of two synclines separated by a median gneissic inlier around Beawar. The synclines are called as Sendra basin in the west and Bhim basin in the east. The prominent polymictic Barr conglomerate in the west and the corresponding Srinagar conglomerate in the east were considered as basal conglomerates of the sequence in SDFB. The eastern basin rocks were classified under Gogunda Group, whereas the western basin rocks were termed Kumbalgarh Group. This simple picture changed with the recognition of several parallel strike faults cleaving the succession into a number of tectono-stratigraphic units with disputable mutual relationship (*see* Mukhopadhyay and Bhattacharyya, 2000). Bhim basin consists mainly of arenite-pelite-carbonate sequence indicating shelf to slope environment, whereas Sendra basin is made of a dominant bimodal volcanic sequence suggestive of oceanic environment. Phulad Ophiolite is found in the western basin. In addition, there are linear belts of quartzite-carbonate-pelite association on either side of the SDFB and their stratigraphic status with respect to the main belt is uncertain. These stratigraphic units are

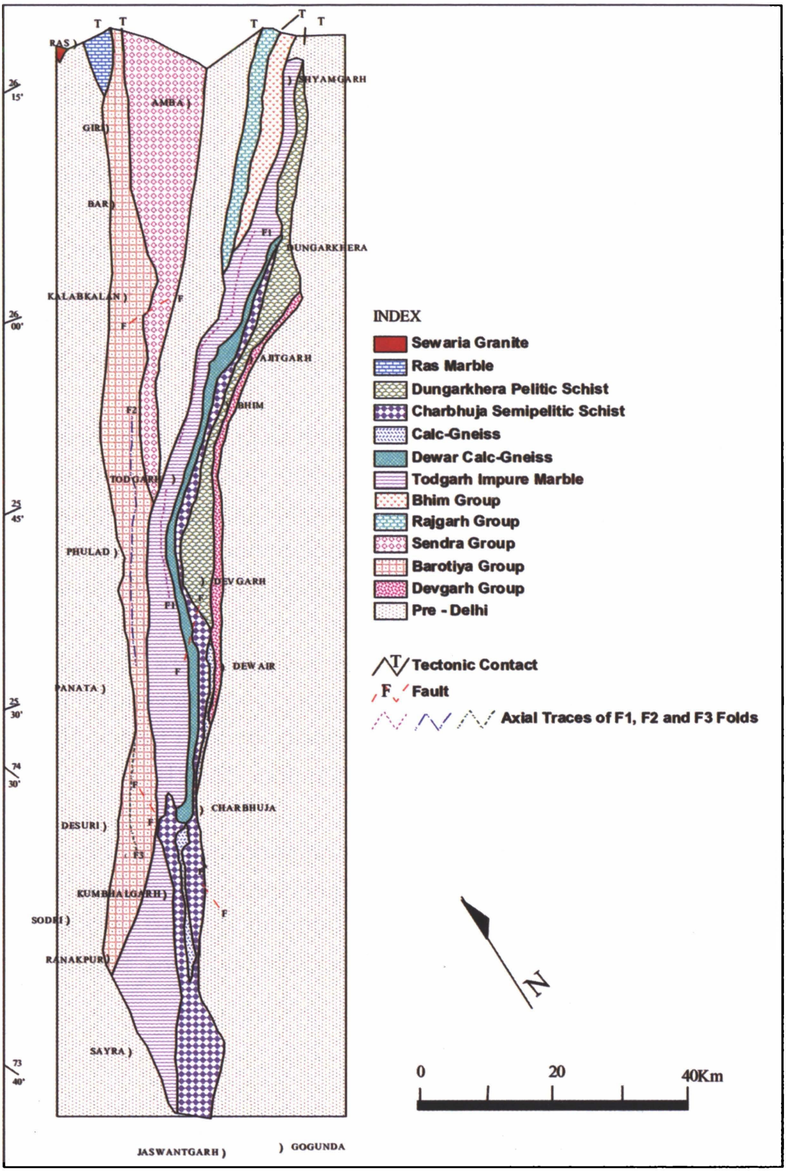

T
T
T
T
T
RAS
26 15'
AMBA
GIRI
SHYAMGARH
BAR
F1
DUNGARKHERA
KALABKALAN
F
F
26 00'
AJITGARH
F2
BHIM
TODGARH
25 45'
PHULAD
DEVGARH
F1
F
DEWAIR
F
PANATA
25 30'
74 30'
F
CHARBHUJA
DESURI
F
F3
F
KUMBHALGARH
F
SODRI
RANAKPUR
SAYRA
73 40'
JASWANTGARH
GOGUNDA
INDEX
Sewaria Granite
Ras Marble
Dungarkhera Pelitic Schist
Charbhuja Semipelitic Schist
Calc-Gneiss
Dewar Calc-Gneiss
Todgarh Impure Marble
Bhim Group
Rajgarh Group
Sendra Group
Barotiya Group
Devgarh Group
Pre - Delhi
T Tectonic Contact
F Fault
Axial Traces of F1, F2 and F3 Folds
N
0
20
40Km

**Fig.3A.24.** Geological sketch map of SDFB (after Gupta et al. 1995).

known by different names such as Gogunda Group, Devgarh Group and Ras Marble. The tectono-stratigraphy of the main SBFB is given below:

| | | |
|---|---|---|
| Delhi Supergroup of South Delhi Fold Belt | Bhim Group<br>Rajgarh Group | Bhim basin (east) |
| | Sendra Group<br>Barotiya Group<br>Basantgarh Group | Sendra basin (west) |

*Basantgarh Group*: Basantgarh, Barotiya and Sendra Groups occur successively from west to east in the western Sendra basin. Basantgarh Group situated on the western flanks of the basin, consists of three litho-tectonic associations: metabasalt, calc-schist, metapelite and quartzite constitute a rift fill sequence; marble and mica schist represent platformal sequence deposited on rifted basement; pillowed metabasalt, basic volcanic breccia, metagabbro, serpentinite, talc-chlorite schist, metagreywacke and metatuff denote arc-trench gap and ophiolite sequences. Metagreywacke is reported to have an imprint of relict blueschist facies of metamorphism. Basantgarh Group therefore forms part of ophiolite melange that is included under Phulad Ophiolite Suite.

*Barotiya Group:* Barotiya (also called Birantia or Birantiya) Group consists of three litho-tectonic units: Barr conglomerate, mica schist, impure marble, subarkose and bimodal volcanics; Narpura marble; and metavolcanics, marble and subarkose. The basal status of Barr conglomerate is in dispute and is now regarded as the top unit of the westward younging succession of Barotiya Group. The polymictic conglomerate is sheared and in tectonic contact with the pre-Delhi gneisses to the west. The bimodal volcanics are mainly tholeiitic metabasalts associated with rhyolite. Rhyodacite is well developed in the Deri-Ambaji area of Gujarat. Locally high-Mg basalts are also found. The bimodal volcanics have unfractionated REE patterns unlike MORB.

*Sendra Group:* Sendra Group is made of metabasalt, marble, subarkose, semipelite and quartzite, with oligomict and polymict conglomerate. This group is tectonically juxtaposed against Bhim Group in the east. Metabasalts are low-K tholeiites that are less alkaline than Barotiya volcanics. Sendra volcanics are not bimodal like Barotiya volcanics.

### *Phulad Ophiolite Suite*

Phulad ophiolite suite (Fig.3A-25) occurs as dismembered linear bodies of epidiorite, amphibolite, pyroxene granulite, metagabbro and ultramafic rocks that are exposed intermittently from Khedbrahma through Kui in Gujarat to Ajmer for 500 km with a width of about 40 km. Several closely spaced shear zones form part of tectonic melange. The shear zones separate Bhim Group (arc-trench gap sequence), Sendra Group (volcanic arc sequence) and Barotiya Group (marginal sea sequence) near Kamblighat. Basantgarh Group represents arc-trench sequence tectonically juxtaposed against the ophiolites.

Intrusive rocks of Phulad ophiolite suite are serpentinites south of Ajmer, diorite-quartz diorite-plagiogranite-tonalite near Ranakpur, and gabbro-norite

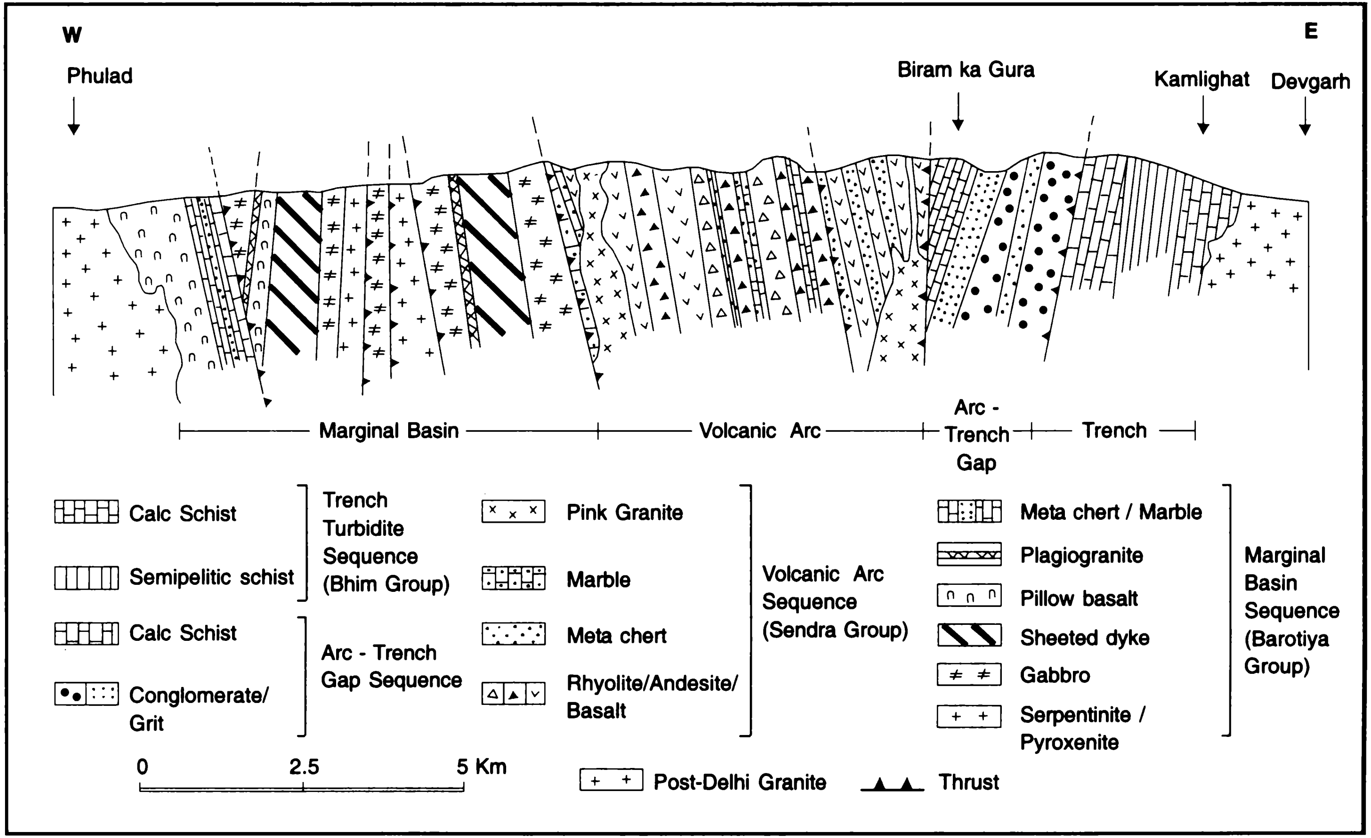

W
E
Phulad
Biram ka Gura
Kamlighat
Devgarh
Marginal Basin
Volcanic Arc
Arc - Trench Gap
Trench
Calc Schist
Semipelitic schist
Trench Turbidite Sequence (Bhim Group)
Calc Schist
Conglomerate/ Grit
Arc - Trench Gap Sequence
Pink Granite
Marble
Meta chert
Rhyolite/Andesite/ Basalt
Volcanic Arc Sequence (Sendra Group)
Meta chert / Marble
Plagiogranite
Pillow basalt
Sheeted dyke
Gabbro
Serpentinite / Pyroxenite
Marginal Basin Sequence (Barotiya Group)
0
2.5
5 Km
Post-Delhi Granite
Thrust

**Fig.3A.25.** Phulad ophiolite – cross-section (after Sinha-Roy, 1988).

bodies associated with the basic granulites of Kui-Chitrasani shear zone forming part of the Phulad shear zone. Ranakpur diorite yields Sm-Nd whole rock isochron of 1012±78 Ma. The oceanic crust of Delhi fold belt was subducted to produce the ophiolite melange, and talc-chlorite-kyanite-grospydite assemblage and glaucophanitic facies association that are interpreted as high-pressure metamorphics typical of subduction zones (Sinha-Roy and Mohanty, 1988; Shamim Khan et al. 2005).

*Rajgarh Group* occurring in the eastern Bhim basin consists dominantly of cross-bedded quartzite, pelitic schist and calc-gneiss metamorphosed in upper amphibolite facies. Rajgarh Group probably represents continental slope facies. Some authors consider Rajgarh Group as older than Bhim Group, whereas some others consider it vice versa. There is another view that Rajgarh Group is correlatable with the supracrustals surrounding Anasagar gneiss and so is pre-Delhi.

*Bhim Group* is a major unit of the eastern belt and consists of pelitic to semi-pelitic schists, calc-silicate rocks and wollastonite bearing impure marble. This assemblage denotes shelf environment.

### Associate Groups of SDFB

There are certain other groups, as mentioned earlier, that are closely associated with SDFB, but occur at its periphery and have uncertain stratigraphic status. These are described below:

*Gogunda Group*: A fairly long and continuous succession of quartzite-pelite-carbonate suite is classified into Gogunda Group that extends from Kishangarh in the north to Himmatnagar in the south. The basal unit at the eastern margin of SDFB consisting of muscovite-biotite schist, amphibolite, calc-silicate rock and quartzite is sheared against the Jharol Group of Aravalli Supergroup. The lithological assemblage that overlies the basal unit is quartzite, biotite schist, calc-silicate rock and marble. Gogunda Group is included in the Delhi Supergroup by some authors, whereas others regard it as pre-Delhi.

*Devgarh Group* consisting of quartzites and pelites occurring as narrow bands within basement gneiss is seen to the east of Bhim Group in the Bhim basin. The stratigraphic position of Devgarh Group is ambiguous.

*Ras Marble* was originally regarded as part of Raialo 'Series,' but is now regarded as part of Delhi Supergroup with Barr conglomerate at the base. It occurs in the strike continuity of Makrana marble. Ras Marble is bounded by granites and migmatites that are believed to be pre-Delhi.

*Ajmer Formation* occurring to the north of Bithur-Pisangan Line near Sambhar Lake consists of quartzites and arkose-pelite-greywacke suite that overlie Anasagar migmatites. The rocks are involved in polyphase deformation and high-grade metamorphism. The succession is regarded as pre-Delhi, providing a link between NDFB and SDFB, or as part of SDFB if its boundaries are extended further north. Others regard Ajmer Formation as a time-transgressive ensemble of pre-Aravalli, pre-Delhi and Delhi lithic units.

## METAMORPHISM

In Alwar basin, P-T conditions are 500-550° C and 3-4 kb as indicated by the assemblage of andalusite-staurolite-garnet-biotite-muscovite. The assemblage of scapolite and chondrodite in marbles is probably the result of thermal imprint of granite intrusion. The Bayana-Lalsot basin is characterised by low-grade metamorphism of greenschist facies. Dual metamorphic zones of andalusite-sillimanite and kyanite-sillimanite types are described from Khetri belt. The kyanite-sillimanite type reflects early regional metamorphism related to pervasive deformation, and the andalusite-sillimanite type is attributed to granitic intrusions. Alternative interpretation of the metamorphic scenario shows that the early low-pressure metamorphism occurred at 550° C at 3 kb followed by medium pressure metamorphism at 600° C and 5 kb.

In the Ajmer-Bhim area, westward increase in metamorphism from staurolite-kyanite zone to sillimanite-muscovite zone is noticed (550° C and 5-6 kb) which culminated in the granulite facies, as seen in the tectonic slices of granulites (~ 650° C and 6 kb) exposed in the Pilwa-Chinwali area (Fig.3A-26). In the south of the belt at Deri-Ambaji and Balaram-Abu Road areas, regional granulite facies metamorphism (900 to 1000°C and 7-8 kb) was overprinted by thermal metamorphism. In SDFB, metamorphism is of intermediate pressure type in low to medium grade, with high-grade rocks occurring in patches. The ophiolite melange (Phulad ophiolite) shows relicts of blue schist facies metamorphism.

### Granite Intrusions

*Sendra-Ambaji granite suite*

Scattered bodies of granite intruding the SDFB and covering an area of 360 x 40 km near Khedbrahma are called Sendra-Ambaji granites. These are essentially granites, granodiorites, tonalites, granitic gneisses and associated

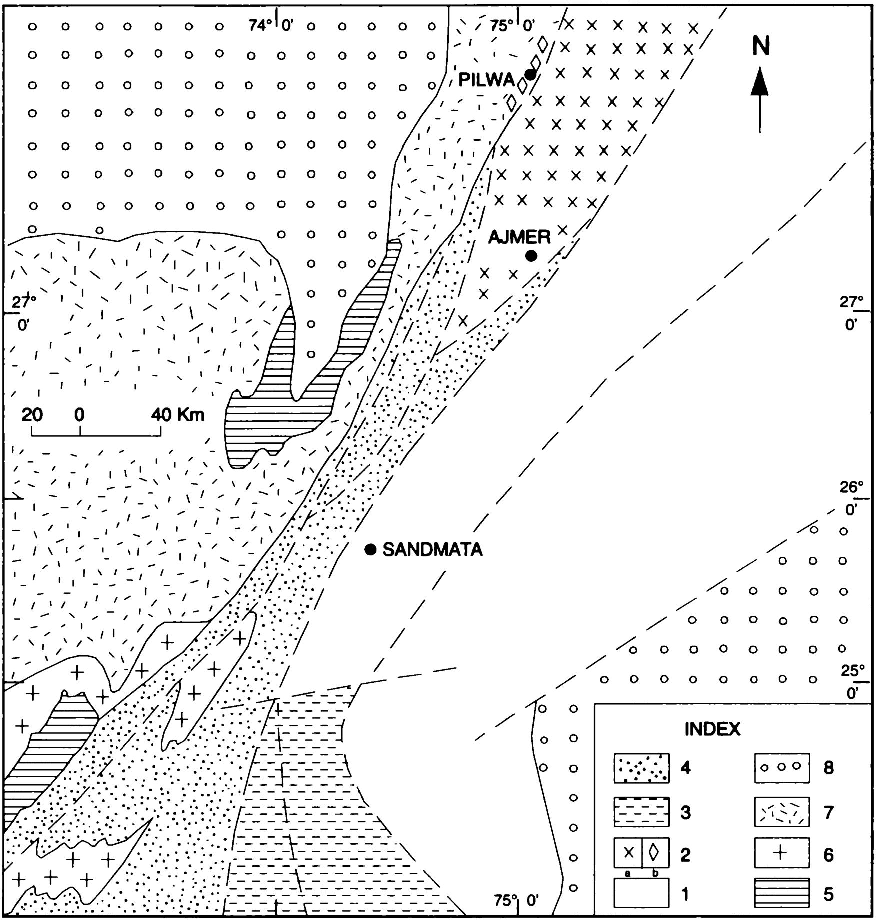


**Fig.3A-26.** **Pilwa-Chinwali granulites in the west of Delhi fold belt (after Fareeddudin, 2000). 1 - Gneissic complex, 2 - (a) Anasagar migmatite; (b) Charnockites, 3 - Aravalli Supergroup, 4 - Delhi Supergroup, 5 - Punagarh Group, 6 - Erinpura granite, 7 - Malani Igneous Suite, 8 - Marwar Supergroup. Dashed lines indicate faults.**

migmatites. Several diapiric and non-diapiric bodies of granite such as Chang, Borwar, Chitar, Jaitpura, Seliberi, Sei, Sadri-Ranakpur etc. form part of this suite, and some of them intrude the Sendra Group. Despite the chemical diversity, the granite suite is probably linked genetically to a single parent magma. Rb-Sr pooled isochron age of these granitic bodies is 850±50 Ma. Pb-Pb age of Deri-Ambaji ores is ~1100 Ma. Rhyolites of Deri area yield ages of ~990 Ma. Rb-Sr isochron age of microgranite from Ambaji is 760±50 Ma, that is close to single zircon age of ~760 Ma of charnockite from Balarampur area. These dates, taken together with the ~1000 Ma age of Ranakpur diorite, indicate that the SDFB evolved during 900-1100 Ma. The imprint of younger granitic activity in Marwar craton is also seen from the ages of 750-800 Ma.

## Neoproterozoic of Marwar Craton

Gneisses with pre-Delhi enclaves of quartzite-carbonate-pelite suite, which were together described as part of BGC by Heron (1953), occur to the west of Phulad Lineament in Marwar craton. They may as well be part of the basement of Marwar craton, unrelated to BGC. Marwar craton consists of Neoproterozoic supracrustal belts of Sirohi, Sindreth and Punagarh that were earlier classified with the upper part of Delhi Supergroup. These are now regarded by some authors as successor basins related to Delhi orogeny. Neoproterozoic granites of Erinpura Suite of batholithic dimensions intrude the Delhi Supergroup to the east of Phulad Lineament and Sirohi Group in the west. These probably constitute stitching granites across the terrain boundary. This event is followed by the extensive and well-known anorogenic felsic magmatism of Malani Igneous Suite (MIS). Stabilisation of the craton was achieved with the emergence of platform basins of terminal Neoproterozoic Marwar Supergroup. This interesting sequence of events is described below:

### Sirohi, Sindreth and Punagarh Groups

*Sirohi Group:* A group of fine-grained sediments of pelite-quartzite-marble suite occurs in a NE trending belt near Sirohi. These deformed and metamorphosed sediments are called the Sirohi Group. The surrounding Erinpura Granite Suite is believed to be either intrusive into or acting as basement for Sirohi Group. Isolated outcrops of metasediments seen within gneisses and

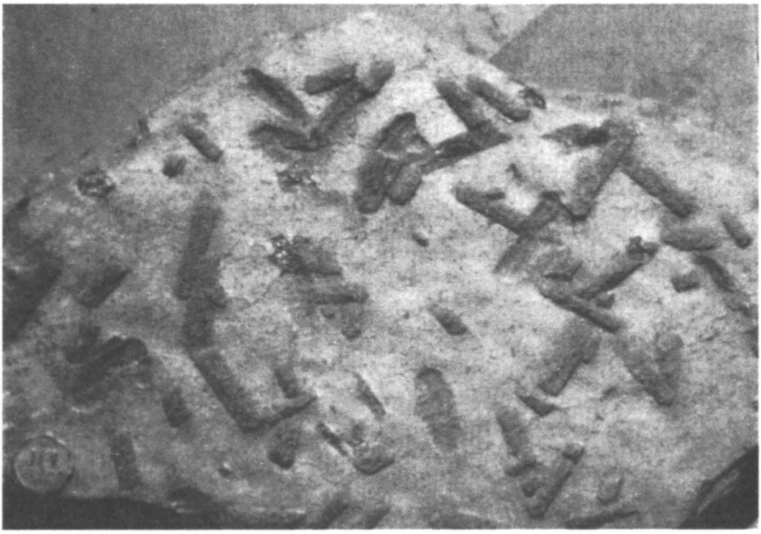


**Fig.3A-27.** Andalusite schist in Sirohi Group (after Roy and Jakhar, 2002, p.242).

granites to the north and south of Sirohi belt are considered either as part of Sirohi Group or as scattered pre-Delhi outliers. Important outcrops of such rocks are Makrana and Ras marbles, Degana phyllites and Didwana quartzites.

Sirohi Group consists mainly of quartz-mica schists, carbonaceous phyllites, dolomitic marbles and calc-silicate rocks. Quartz-biotite-muscovite schists contain porphyroblasts of andalusite (Fig.3A-27) and garnet around the intrusive Balda granite. Tremolite-actinolite schist interbands are seen within impure marble. Sirohi Group shows a simple deformational pattern of a single foliation and lineation in contrast to the complex deformation of Aravalli and Delhi fold belts. Metamorphism of the belt ranges from greenschist to amphibolite facies. The age of the belt is indirectly known from the Rb-Sr date of Erinpura granite at ~850 Ma.

*Sindreth Group:* A thick sequence of weakly deformed and feebly metamorphosed arenaceous sediments, accompanied by bimodal volcanics with a larger felsic component, unconformably overlies the deformed and metamorphosed Sirohi Group and is classified under Sindreth Group. The sediments of this group form cycles of conglomerate, quartzite, shale and phyllite. Amygdular basalts are seen as several flows with interflow sediments of quartzite and shale. Since these basalts are situated in the area of Deccan Trap, it becomes difficult to distinguish them from Deccan basalts. Felsic volcanics and pyroclatics are more abundant than mafic flows, and have been compared with Malani Igneous Suite. Sindreth basalts give TIMS U-Pb age of ~765 Ma.

*Punagarh Group:* An oval-shaped outcrop near Punagarh along with many isolated exposures in the vicinity, consisting of shale, phyllite, mica schist and quartzite along with a few flows of pillowed metabasalt, amygdular basalt, volcanic breccia, tuff and bedded chert constitute the Punagarh Group. Interflow sediments of quartzite and slate are also noticed. These rocks, like the Sindreth Group, are feebly deformed and weakly metamorphosed. Punagarh Group overlies the Sirohi Group and is in turn overlain by Marwar Supergroup.

### Granite Intrusions

There are several bodies of granite that intrude the various lithostratigraphic units like the pre-Delhi gneisses and supracrustals, Delhi Supergroup, Sirohi Group and Punagarh-Sindreth Groups in Marwar craton. Most of them have intruded in the time span of 730 to 870 Ma, as evidenced by a cluster of Rb-Sr ages. These granitic suites are described below:

*Erinpura Granite Suite:* This granite suite occurs in a belt 325 km long and 3 to 15 km wide along the western margin of SDFB and Sirohi belt and includes Mt.Abu and Sewariya granites. The granitic suite consists of many phases identified by mutual relationships, deformational features and enclave types. The granitic suite is commonly porphyritic, but locally gneissic. The composition on the average is granite, but it varies from normal granite to granodiorite. Rapakivi texture is locally seen. *Sewariya granite* forms the largest pluton (35 x 6 km) of the Erinpura granite suite and is situated between Ras marble and Barr conglomerate to the west of SDFB. It is a peraluminous, S-type granite consisting of early porphyritic granite and late homophanous granodiorite. The granite is noted for tungsten mineralisation.

*Balda Granite*: This non-porphyritic leucogranite hosting tungsten mineralisation occurs as phacoliths, dykes and apophyses. It is fractionated, I-type granite that was regarded earlier as a part of Erinpura granite, but is now known to be a younger granite that intrudes Sirohi Group. Similar homophanous leucogranite granite in Gujarat is called *Idar* granite.

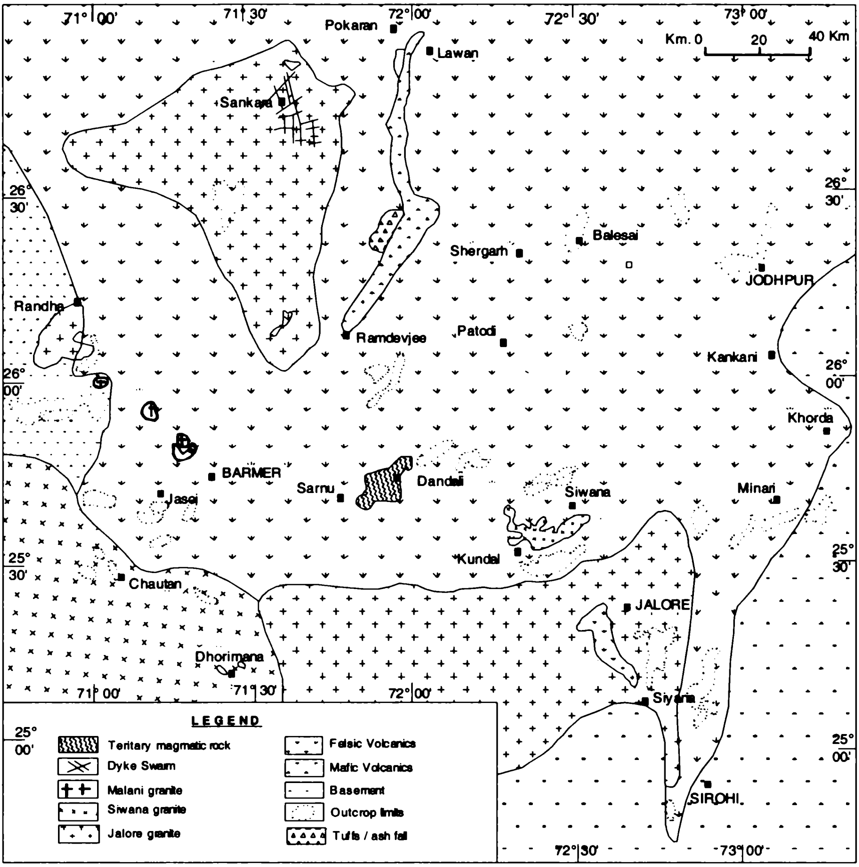
*Degana Granite*: It is a topaz bearing Rapakivi granite and granite porphyry that is known for multiple episodes of tungsten mineralisation. The granite is strongly peraluminous and geochemically specialised with enrichment of Rb, Li and F and depletion of Sr.

*Godhra Granite*: This is porphyritic granite to granodiorite with associated pegmatite and aplite, and intrudes the Champaner and Lunavada Groups of Aravalli Supergroup. It is a peraluminous, S-type granite, enriched in Zr. A rare basic plug, probably related to Deccan volcanism, is seen within Godhra granite.

*Lamprophyre:* Lamprophyre dykes trending WNW-ESE to E-W are reported from SDFB. These may correlate with the alkaline magmatism of Deccan Trap and may be unrelated to Proterozoic evolution.

### Malani Igneous Suite

Malani Igneous Suite (MIS) forms the largest felsic volcanic province of India (51000 km$^2$) and the third largest in the world. It represents a major event of anorogenic (A-type), within-plate magmatism in the Neoproterozoic (680-780 Ma) of Marwar craton (Fig.3A-28). MIS occurs to the west of Aravalli Mountain as tors, inselbergs and scattered hummocks below a blanket of wind blown sands and sand dunes in Thar Desert. It occurs commonly as bimodal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Km. 0 20 40 Km
Pokaran
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Ramdevjee
Patodi
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Khorda
BARMER
Jasai
Sarnu
Dandali
Siwana
Minari
Kundal
Chautan
JALORE
Dhorimana
Siyana
SIROHI
26° 30'
26° 00'
25° 30'
25° 00'
LEGEND
Teritary magmatic rock
Dyke Swarm
Malani granite
Siwana granite
Jalore granite
Felsic Volcanics
Mafic Volcanics
Basement
Outcrop limits
Tuffs / ash fall

**Fig.3A-28.** Malani Igneous Suite (after Bhushan, 2000).

volcanics with a very large felsic component, ring intrusions, and radial dykes. The volcanics are mainly rhyolite, perlite and trachyte (with minor basalt) that are intimately associated with volcaniclastics like welded tuff and explosion breccia. The ring intrusions are the peralkaline Siwana granite, mildly peralkaline Jalor granite, peraluminous Tusham granite, Jhunjhunu granite, and Kirana granite of Pakistan. Dykes like felsite and porphyry form the final phase of Malani magmatism. Mesozoic-Cenozoic alkaline igneous complexes of Mundwara, Sarnu-Dandali and Tavidar-Karara that occur nearby within the same igneous province are excluded from the Neoproterozoic MIS, since these alkaline complexes are associated with Deccan Trap volcanism that is also manifested in the same area of Marwar craton. They are described under Chapter 9.

MIS is underlain by metasediments of Sirohi and Sindreth Groups and the younger granitoids of Delhi Supergroup, particularly the Erinpura and Sendra-Ambaji granite suites, and pre-Delhi gneisses. Some authors consider Sindreth and Punagarh Groups as homotaxial with MIS (*see* Sharma, 2004).

Volcaniclastic boulder conglomerate and arkose define the base of MIS at Sindreth, Diri and Kankani near Jodhpur where they overlie the quartzite and phyllite of Sirohi Group with angular unconformity. Mount Abu granite (800± 50 Ma) underlies the MIS at Siyara, and xenoliths of Abu granite are abundant in the overlying rhyolites. The rhyolites are dated by Rb-Sr method at 730-750 Ma by various workers. MIS is unconformably overlain by the glacial Pokaran bed (~580-680 Ma) or by other sediments of Marwar Supergroup (Vendian to Eocambrian).

MIS lies within a regional gravity high caused by the uplift of lower crust and upper mantle. Locally, granite bodies cause gravity lows. Arcuate structures of MIS, seen in satellite imageries, are confirmed by gravity and magnetic data. Magnetic and radiometric surveys confirm the presence of acidic intrusions. Tusham area shows high heat flow values (96 $mWm^{-2}$), which reflect the nature of HHP (high heat producing) granite. Jhunjhunu granite also indicates high heat flow from upper mantle. Geo-electric and isostatic models indicate the presence of transitional crust in the area.

### *Nomenclature*

Blanford (1877) introduced the term 'Malani Beds' for a series of volcanic rocks in the erstwhile Marwar or the princely State of Jodhpur. The volcanics were later called as 'Malani volcanic series' or 'Malani system'. Krishnan and Jacob (1956) named the rhyolites and associated granites as 'Malani Igneous Suite' (MIS), and this terminology has a large following. Roy (1988a) classified these rocks under 'Malani Group', and since these rocks largely form an igneous ensemble, the terminology of Malani Igneous Suite, as acceptable to stratigraphic codes, appears very appropriate. Overviews of MIS are available in Pareek (1981), Kochhar (1984, 2000), Bhushan (2000), and Bhushan and Chandrasekharan (2002).

### ***Rock Types of Malani Igneous Suite***

MIS is divided into three phases of igneous activity based on field relations, mode and type of magmatism as well as texture and composition of rock types, as shown below:

3. Dyke swarms: Gabbro, dolerite, granite, aplite, rhyolite, andesite, trachyte, porphyry etc.
2. Granitoids: Malani, Jalor and Siwana granites
1. Bimodal volcanics: Rhyolite, rhyodacite, dacite and trachyte, basalt and trachy-andesite

*Bimodal volcanics*: Tholeiitic or alkaline lavas, often interleaved with widespread felsic flows, are known from Diri, Gurupratap Singh and Manihari areas. Basalts are mostly amygdaloidal and are rarely pillowed. Some basaltic andesites contain olivine phenocrysts. Pyroclastics and acid lava flows form the most voluminous unit of MIS. The acid volcanics are mainly rhyolite, rhyodacite, dacite, trachyte and pitchstone. Pyroclastics are welded and lapilli tuffs, vitric and lithic tuffs, ignimbrites, obsidian, agglomerates and volcanic breccias. Volcanic conglomerates are also closely associated. Felsic volcanism occurred in three stages, firstly as pyroclastic explosions, next as acid lava flows, and finally by another pyroclastic ash fall. Acid volcanics of the second stage are the most voluminous. Flow structure, glassy textures and columnar jointing are common.

Malani rhyolites are rich in $SiO_2$ (75%), total Fe (7%), $Al_2O_3$ (>12%) and $K_2O$ (10%). They have less than 12% of normative mafic minerals. Rhyolites are of two types, peraluminous and peralkaline. Both types show LREE enrichment, flat HREE and strong Eu anomaly. The peralkaline types are enriched in most trace elements except Ba. A few peralkaline rhyolites belong to comendite and pantellerite clans.

*Granitoids:* About 15 granite plutons covering a total area of 8000 sq. km occur in MIS. Important granites are the biotite bearing Jalore Granite, riebeckite-aegirine bearing Siwana Granite and hornblende bearing Malani Granite.

*Jalor Granite* consists of seven plutons of which the Sankra pluton is the largest covering 3700 $km^2$. In Sankra pluton, the magmatic activity commenced with outpouring of peraluminous rhyolite, followed by granite intrusion, and later injection of felsic to mafic dykes. The granite has two varieties, pink biotite granite as the main, and grey granite as bands and patches in pink granite. Pink granite shows rapakivi texture and ranges in composition from quartz syenite to alkali granite. Besides the essential constituents, the granite contains augite, hypersthene, hornblende, biotite and even fayalite. The granites are rich in silica and alkalis as well as Zr, Ga, Y, U and Th. They are enriched in LREE and depleted in HREE. These granites are 'within plate', A-type granite derived by high temperature partial melting of lower crust.

*Siwana Ring Complex* consists of six granitic plutons covering an area of 1100 $km^2$. The main Siwana ring complex has formed by the collapse of volcanic caldera (800 $km^2$), followed by the intrusion of ring dykes of peralkaline granite along its periphery. The main magmatic phases of Siwana granite with their basal felsic volcanics and mafic dykes are (i) porphyritic granite,

(ii) leucogranite and pegmatite, and (iii) microgranite and granite porphyry. The granite contains riebeckite, arfvedsonite and aegirine, and is mainly of peralkaline, hypersolvus type. The granites are rich in silica, titania, alkali and total iron, besides Nb, Zr, Y, La and Ca. They show high total REE content with little fractionation and strong Eu anomaly. Siwana granite is probably derived by high temperature melting of anhydrous granulite source region, with significant modification by crustal contamination.

*Tusham (Tosham) Ring Complex* of Haryana (Kochhar, 1983) consists of rhyolite and granite intruding andalusite bearing carbonaceous mica schist of Sirohi Group. Granite fragments occur as xenoliths in rhyolite. This ring complex is well known for its unique Cu-(Au)-Ag-Sn-Bi-In mineralisation. Geochemically the Tusham and Kharak granites straddle the fields of A and S-type. The Tusham granite is dated by Rb-Sr method at 770 Ma, but recent Ar-Ar geochronology suggests that it may be 800 Ma old.

*Malani Granite* consists of two plutons of hornblende granite covering 70 $km^2$ near Barmer. It is porphyritic granite rich in hornblende and grades into alkali granite porphyry.

*Dykes*

A profuse dyke system of different compositions forms part of MIS, although it has to be distinguished from the mafic dykes related to Deccan Trap. Two principal directions of dykes are NW and NE. The dykes cut across Malani rhyolite, Abu granite, basalt and granite of MIS. Most dykes are dolerite, but some are microgranite, andesite, rhyolite porphyry.

*Age*

MIS gives a range of ages from 725 to 745 Ma. Malani granite and rhyolite ages are 745±5 Ma, Tusham 732±41 Ma, Siwana 727±5 Ma and Jalor 725± 7 Ma. On the average, the age of MIS may be reckoned at ~730 Ma.

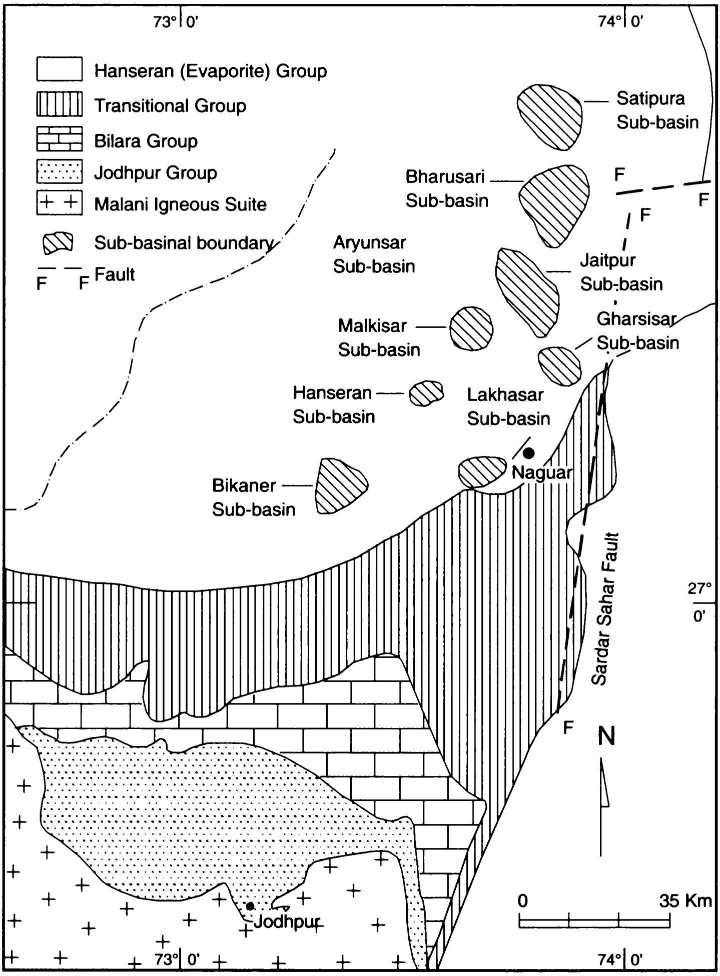
## Evolution of MIS

Anorogenic activity commenced in the Marwar craton after the cessation of deformation and metamorphism of Sirohi Group and Erinpura granitic magmatism around 850-900 Ma. Volcano-sedimentary platform basins of Sindreth and Punagarh developed on the stabilised craton. A widespread event of anorogenic magmatism ensued with the development of MIS, starting with bimodal basalt-rhyolite volcanism, followed by peralkaline granitic ring complexes and felsic-mafic dykes during the period 720-750 Ma.

There are different views on the evolution of MIS. There seems to be a consensus that it is fracture-controlled continental rift type magmatism. This is attributed to hot spot or mantle plume activity (Kochhar, 1984). Others attribute it to doming before supercontinental break up, or to epeirogenic uplift. Bhushan (2000) related this to Pan-African magmatism, whereas Sinha-Roy et al (1998) suggest that it is the result of distension following the subduction of oceanic or transitional crust during Delhi orogeny (SGFB).

## Neoproterozoic Marwar Basins

A typical platformal sequence, characterised by the presence of evaporites, occurs in a series of unmetamorphosed and undeformed sedimentary basins located to the west of the Aravalli mountain in the plains of Marwar craton


73° 0'
74° 0'
Hanseran (Evaporite) Group
Transitional Group
Bilara Group
Jodhpur Group
Malani Igneous Suite
Sub-basinal boundary
F F Fault
Satipura Sub-basin
Bharusari Sub-basin
Aryunsar Sub-basin
Jaitpur Sub-basin
Malkisar Sub-basin
Gharsisar Sub-basin
Hanseran Sub-basin
Lakhasar Sub-basin
Bikaner Sub-basin
Naguar
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Jodhpur
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74° 0'

**Fig.3A-29.** Marwar basins (after Das Gupta, 1996).

(Fig.3A-29). The sediments, about two km thick, are essentially arenites, carbonates, evaporites and reddish argillites belonging to Neoproterozoic to Eocambrian Marwar Supergroup. The supergroup is well known for potash bearing halite and gypsum deposits. The large (750 x 300 km) and asymmetrical Marwar basins are bounded in the east by the N-S trending Sardarsahar Fault and in the south by the Pokaran Ridge. In the north and west, the basins are concealed under Tertiary and Recent sediments. Marwar sediments have gentle rolling dips that define broad synforms, domes or monoclines having NNE or NNW trends, and this may reflect basement configuration. The tectonic setting of Marwar basins is described as 'foreland slope' basins of the rising Aravalli Mountain. Marwar Supergroup unconformably overlies Malani Igneous Suite, Sirohi Group as well as Aravalli and Delhi Supergroups. The supergroup was correlated with upper parts of Vindhyan Supergroup and hence called earlier as Trans-Aravalli Vindhyan. These sediments were also compared to the Saline 'Series' of Salt Range in Pakistan, because of the presence of salt pseudomorph shales and stromatolites in carbonates. Tertiary fossils suggesting Tethyan affinity have been reported intermittently from Marwar sediments, but their *in situ* disposition has always been a matter of serious debate. Most authors now concede that the Marwar basins are of terminal Proterozoic to early Cambrian age.

Marwar Supergroup is deposited in two separate basins viz., the large Nagaur basin together with many isolated sub-basins in the north, and the small Birmania basin. Nagaur basin comprises an unfossiliferous marine sequence that is divided into three groups, namely, Jodhpur Group, Hanseran Group (= Bilara Group) and Nagaur Group. The generalised lithostratigraphy of Marwar Supergroup (Das Gupta et al. 1988) is tabulated below:

| Permo-Carboniferous | |
|---|---|
| Nagaur Group | Sandstone, siltstone, shale, local basal conglomerate |
| Hanseran Group (=Bilara Group) | Dolomite, magnesite, anhydrite, halite, potash salts, shale, stromatolitic limestone, dolomite, chert |
| Jodhpur Group | Sandstone, shale, limestone, chert |
| Basement | |

**Nagaur Basin**

*Jodhpur Group*: The basal unit is the Pokaran boulder bed, about 3 m thick, consisting of boulders, cobbles and pebbles of Malani rhyolite, granite, syenite, Delhi quartzite etc. enclosed in a brownish clayey to silty matrix. Its origin is debatable since some workers believe it to be a glacial or glaciofluvial deposit of Neoproterozoic glaciation, whereas others believe it to be aeolean deposit. The boulder bed is overlain by shale, siltstone and pebbly sandstone having a profusion of sedimentary structures like ripple marks, cross bedding, flute and groove casts, and rib-and-furrow structures. Disputed brachiopod fossil Orthis is reported from these sediments. Jodhpur Group displays six lithofacies from braided river, beach and lagoon to shelf.

*Bilara Group*: It essentially consists of limestone and dolomite with intercalations of shale, siltstone and pebble beds. Carbonate rocks containing stromatolites are comparable to those of Salt Range in Pakistan. Foraminifera, ostracodes and micro-molluscs characteristic of Tertiary are reported from the carbonate sequence, but whether they are indigenous to the host rock or not is questionable. Carbon isotopic studies, however, suggest Neoproterozoic to Eocambrian (Vendian to Tommotian) age. These studies also indicate an earlier frigid climate followed by a later warmer climate.

*Hanseran Group*: It is commonly known as Hanseran Evaporite Group, but such a trinomial nomenclature is not acceptable to stratigraphic codes. The group comprises stratified chemical precipitates of halite and potash salts (polyhalite, sylvite, carnallite) in cyclic to rhythmic deposits alternating with stromatolitic dolomite, magnesite, anhydrite, glauconite and clay. The thickness of the sequence varies from 100 to 650 m and a maximum of seven halite cycles are interpreted from sub-surface data (Das Gupta, 1996).

Hanseran and Bilara Groups are homotaxial facies variant of one another. Both have the same stratigraphic position between the Jodhpur and Nagaur Groups. Bilara carbonates facies show gradual facies variation from sulphate-rich to chloride-rich evaporite facies. Further, Hanseran and Bilara Groups contain similar type of non-phosphatic stromatolites. It is possible that the progressive shallowing of the carbonate basin together with development of aridity would have led to the formation of the evaporite basin.

*Nagaur Group*: It consists mainly of a variety of sandstones with a basal conglomerate. The basal conglomerate contains assorted clasts of dolomite, chert, sandstone, felspar and quartz. Red mottled sandstone interlayered with shale and siltstone overlies the conglomerate. The top unit contains shale, marl, siltstone and pebbly sandstone.

### Birmania Basin

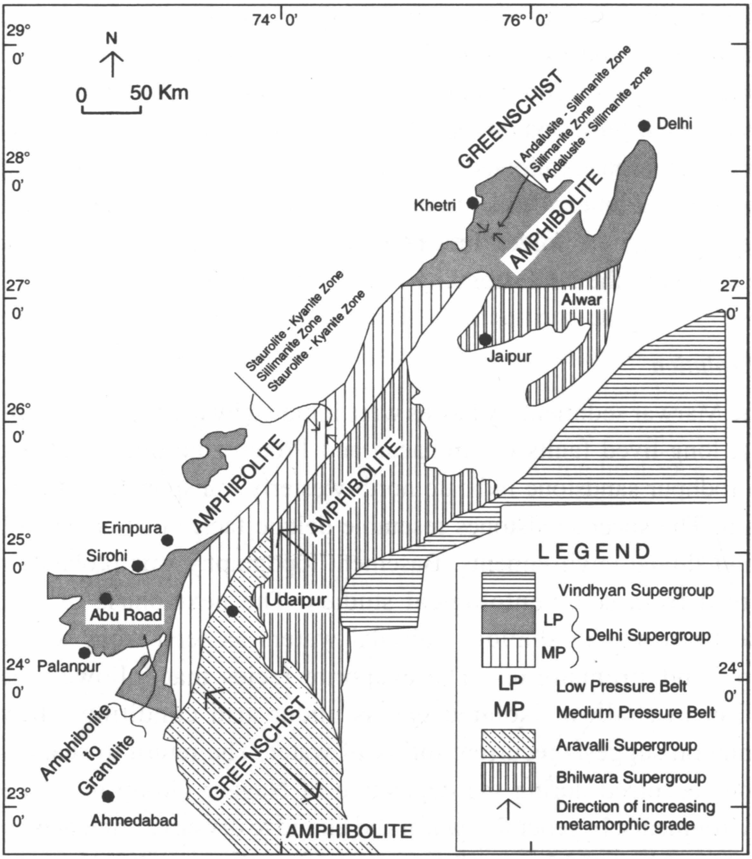
This oval-shaped basin having an area of 100 sq. km is located to the SW of Nagaur basin. It comprises two main formations dominated by sandstones and carbonates. The sandstone formation is correlated with the Jodhpur sandstone of Nagaur basin. It consists of lower shale followed by a variety of sandstones and a 'grit' bed on top. The overlying carbonate formation consists of basal 'needle' shale, followed by cherty and dolomitic limestone, phosphorite and sandstone varieties. Unlike in the Nagaur basin, the homotaxial sediments of Birmania basin are folded into recumbent and doubly plunging folds that may be related to the NNE trending faults in the basin.

### *Basin Evolution*

The Marwar sedimentary basins were initiated by the reactivation of NNW trending, long-lived faults of Archaean and Proterozoic times. Palaeocurrent data on Jodhpur sandstone indicate north-westerly transport from the Aravalli Mountain. The sheet sandstones resemble deltaic facies that changed later to beach and fluvial environments. Basement topography was probably rugged as inferred from sedimentological studies. The next phase of carbonate sedimentation was in shallow, subtidal waters as seen from sedimentary structures and stromatolites. The evaporite facies that followed indicates deposition in shallow, isolated basins under arid conditions. Rhythmic sedimentation suggests recurrent influx of water. The return to shallow water conditions occurred during the deposition of Nagaur Group in tidal to subtidal environments. In general, a warm and humid to dry environment is assumed for the deposition of Marwar Supergroup, though an early phase of global Neoproterozoic glaciation is known and perhaps signalled by the Pokaran boulder bed.

## REGIONAL METAMORPHISM

Metamorphic facies map of Mewar craton is given in Fig.3A-30. A striking feature of the map is increase in metamorphic grade from east to west in the central part of the craton, viz. greenschist facies Hindoli Group (HG) in the east, amphibolite facies Mangalwar Complex (MC) in the middle and amphibolite-granulite facies in Sandmata Complex (SC) to the west. These variations are perceptible across megalineaments, viz. Jahazpur thrust between HG and MC, and Delwara Lineament between MC and SC. Sandmata Complex shows polyphase metamorphism with an early counter-clockwise P-T-t path, superposed by clockwise ITD path signifying subduction and collision. An overall anti-clockwise P-T-t path was also suggested in support of magmatic underplating model. Sandmata Complex was probably formed around 1700 Ma during Aravalli orogeny. There is also a progressive increase in metamorphism from near the northern closure of Aravalli fold belt towards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GREENSCHIST
Andalusite - Sillimanite Zone
Sillimanite Zone
Andalusite - Sillimanite zone
Delhi
Khetri
AMPHIBOLITE
Alwar
Jaipur
Staurolite - Kyanite Zone
Sillimanite Zone
Staurolite - Kyanite Zone
AMPHIBOLITE
AMPHIBOLITE
Erinpura
Sirohi
Abu Road
Palanpur
Udaipur
Amphibolite to Granulite
Ahmedabad
GREENSCHIST
AMPHIBOLITE
LEGEND
Vindhyan Supergroup
LP
MP
Delhi Supergroup
LP Low Pressure Belt
MP Medium Pressure Belt
Aravalli Supergroup
Bhilwara Supergroup
Direction of increasing metamorphic grade

**Fig.3A-30.** Metamorphic facies map of Mewar craton (after Srikarni, 2003, p.55).

Sandmata Complex with a jump across the Nathdwara fault. Similarly, there is an increase from greenschist to granulite grade in southern part of Aravalli belt in Banswara and Jagpura areas possibly around remobilised basement domes. North Delhi fold belt has variable metamorphic grades associated with numerous faults and later granitic intrusions. The Pilwa-Chinwali granulite boudins close to the margins of NDFB are related to orogenic episode at ~1430 Ma. The granulites were brought to the surface along Phulad Lineament.

South Delhi fold belt is broadly divisible into a low-pressure belt in the west and a medium-pressure belt in the east, with a median basement near Beawar. The low-pressure belt may be related to the linear belt of Sendra-Erinpura granites. Granulite metamorphism in Balaram-Abu Road area shows clockwise P-T path and post-peak ITD suggesting crustal thickening by subduction to the west marked by Phulad ophiolite and collision evidenced by the emplacement of Sendra-Erinpura granites during Delhi orogeny at 1000-1100 Ma. The granulites are uplifted along Kui-Chitrasani Lineament forming the southern extension of the main Phulad Lineament.

The overall metamorphic pattern of Mewar craton is related to subduction during Aravalli and Delhi orogenies producing granulites at depth that were exhumed along crustal scale lineaments. The collage of metamorphic blocks exposed in the surface is a result of exhumation along different faults at different times.

## GEOPHYSICAL STUDIES

The striking gravity high of ~80mGal short wave length Bouguer anomaly corresponds to the Aravalli Mountain surrounded by plains on all sides. (Fig.3A-31a) This anomaly coincides with the 'major horst' described by L.L.Fermor in 1930. The anomaly is caused by the density contrast of

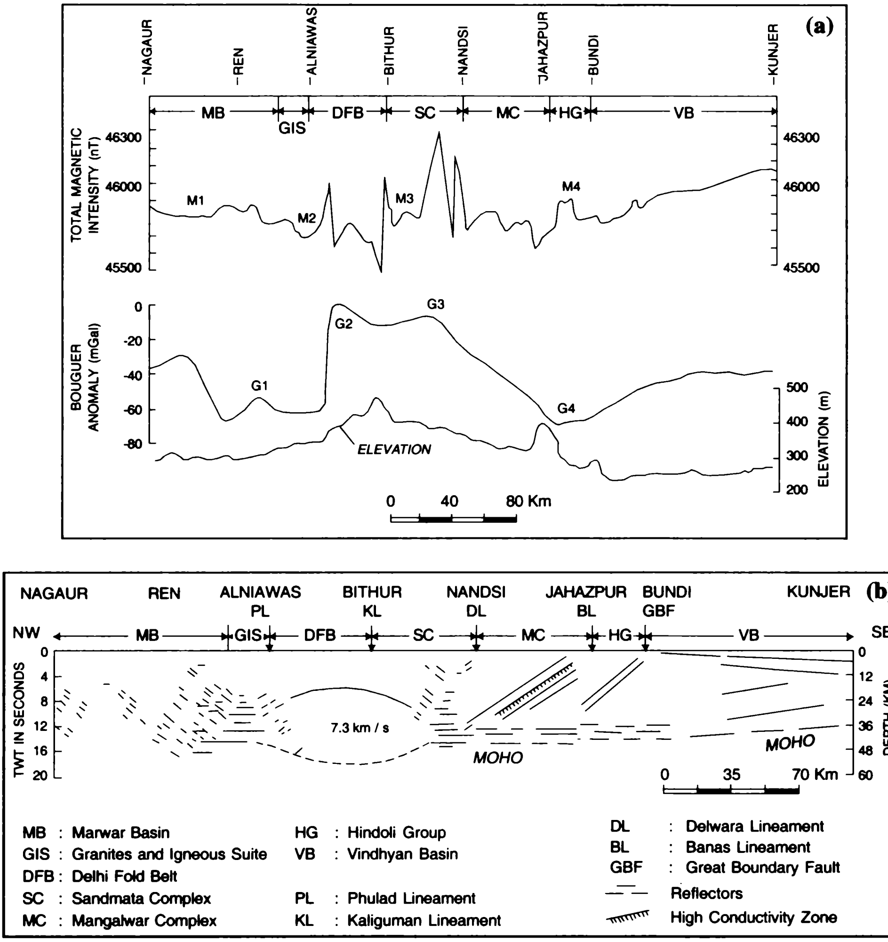


**Fig.3A-31.** (**a**) Gravity-magnetic-topographic profiles along Nagaur-Jhalawar transect (after Mishra et al. 1995). (**b**) Crustal seismic reflection profile along Nagaur-Jhalawar transect derived from migrated stack section (after Tewari et al. 1998).

0.2 gm/cc between the higher density rocks of the fold belt and the lower density of the basement gneisses. This difference is also indicated broadly by magnetic anomalies that are however variable in detail. Seismic reflection profile along the Nagaur-Jhalawar Transect (Fig.3A-31b) displays opposing dips of reflectors along Phulad and Delwara Lineaments that mark subduction-collision zones. Another reflector zone dipping NW coincides with Jahazpur Thrust that marks a major zone of dislocation between the Bundelkhand and Mewar cratons. The thrust has probably formed sympathetically to the Aravalli 'suture zone'. Magneto-telluric studies along the Nagaur-Jhalawar transect have also clearly brought out this high reflector. Seismic reflection section also imaged a mid-crustal reflector in the form of a dome under Delhi belt and Sandmata Complex. This dome coincides with the top of a high velocity layer (7.3 km/sec) above the Moho. The depth to Moho varies between 38 to 48 km as determined from dips of seismic reflectors and by gravity modelling.

## TECTONIC EVOLUTION OF ARAVALLI C RATON

### Archaean Crust

The earliest geological event in the craton is the generation of TTG gneisses at ~3300 Ma from LREE depleted mantle source, possibly through two-stage melting and fractionation into tholeiites and tonalites. Al-rich paragneisses, low-Mg marbles and quartzites of QCP suite occur as scattered enclaves in TTG gneisses, suggesting that stable continental crust evolved in the craton by about 3000 Ma. Remnants of amphibolite, ultramafic rocks and BIF constituting a dismembered greenstone cycle are also found within TTG gneisses. Intrusion of granitoids (Untala, Gingla etc.) and mafic dykes (Mavli) complete the first cratonisation event at ~2800 Ma. The TTG gneisses are called as Mewar Gneiss and the enclaves as Jagat Group, together constituting BGC-I of Gupta (1934). The next major cratonisation event occurred at ~2500-2600 Ma when Berach Granite and associated GAG gneisses (BGC-II) were formed by melting and mixing of juvenile and crustal (BGC-I) components. Large suites of paragneisses, quartzites, marbles, calc-silicate rocks and amphibolites belonging to Bhilwara Group of Raja Rao et al. (1971) occur as enclaves in the type area of Mangalwar Complex (BGC-II).

Sinha-Roy et al. (1998) accepted the nomenclature of Mangalwar Complex by Gupta et al. (1997) to denote the entire BGC of Heron (1953). They identified remnants of early or primary greenstones rich in mafic-ultramafic rocks and BIF (Sawadri Group), and late or secondary greenstones rich in greywackes, volcanics and cherts (Tanwan Group) in the area to the north of Nathdwara. The greenstone remnants are intruded by early tonalites and late potassic granites. Other authors view the greenstones as higher grade metamorphics of Aravalli Supergroup exposed to the north of Nathdwara. Basement granulites of Sandmata Complex are uplifted from deeper crust during later thermal events. Sinha-Roy (2000) suggested that Hindoli Group developed as ensialic rift at the edge of Bundelkhand craton. Hindoli Group was equated with secondary greenstones that were intruded by the Archaean Berach and Jahazpur granites. Hindoli Group was correlated with Mahakoshal Group of CITZ. The age of Hindoli Group is now known to be Palaeoproterozoic (~1800 Ma), similar to that of Mahakoshal Group. The unconformably overlying Jahazpur Group that formed in a narrow continental rift was equated with Bijawar, Gwalior and Jungel Groups of Bundelkhand craton. It is also possible that the Hindoli and Jahazpur form part of the Aravalli sequence. Hindoli Group is visualised as pre-Aravalli by some authors. There is therefore some ambiguity in its tectonic evolution.

## Proterozoic Aravalli-Delhi Orogen

The earlier geosynclinal hypothesis of evolution of Aravalli-Delhi orogen (Gupta et al. 1997) has now given place to plate tectonic models (Sychanthavong and Desai, 1977; Sinha-Roy, 1998; Sugden et al. 1990; Volpe and Macdougall, 1990; Tewari and Vijaya Rao, 2003). The orogen consists of Palaeoproterozoic Aravalli fold belt and Mesoproterozoic Delhi fold belt involved n two separate orogenies. Sen (1981) considered BGC as a microcontinent separating the Aravalli sea in the west and the Bhilwara marginal sea in the east. Aravalli belt was formed by deformation of arc sediments and arc-trench gap sediments into an island arc. After the Aravalli sea was subducted, a new ocean (Delhi ocean) was filled with sediments in the shelf to slope and arc-trench region. Delhi belt was formed by the closing of Delhi sea by folding and thrusting. According to Sharma (1995), the fold belts were formed in continental rifts and deformed by crustal delamination and magma underplating in an A-subduction regime (Fig.3A-32).

Roy (1998a) visualised three stages of evolution of Aravalli basins (Fig.3A-33) corresponding to three sedimentary cycles. The rift basins were linked at a triple junction and had one or more failed arms. The earliest cycle was Hindoli Group with triple junction near Chittorgarh, the next was Delwara Group with triple junction near Nathdwara, and the third was Bhilwara basin as an aulacogen with important Pb-Zn mineralisation. The third cycle was coeval with Udaipur Group. Deep-water facies of Jharol Group was deposited in graben and half-graben. Ultramafic bodies were emplaced in fractures at different periods of anorogenic magmatism and were not ophiolites. Instead of plate tectonics, inversion of ensialic basins was advocated. High-grade metamorphism

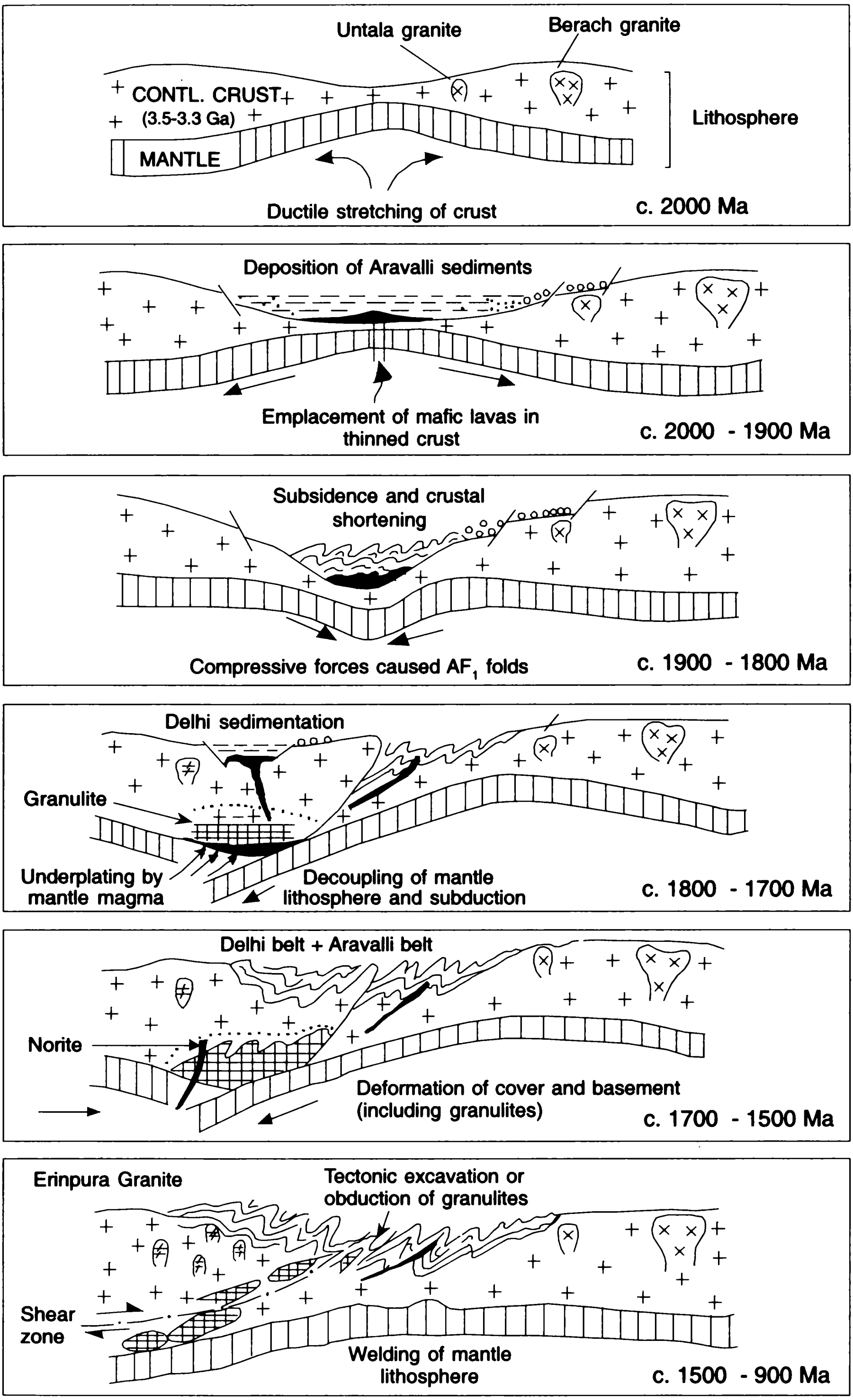

Untala granite
Berach granite
CONTL. CRUST
(3.5-3.3 Ga)
MANTLE
Lithosphere
Ductile stretching of crust
c. 2000 Ma
Deposition of Aravalli sediments
Emplacement of mafic lavas in thinned crust
c. 2000 - 1900 Ma
Subsidence and crustal shortening
Compressive forces caused AF$_1$ folds
c. 1900 - 1800 Ma
Delhi sedimentation
Granulite
Underplating by mantle magma
Decoupling of mantle lithosphere and subduction
c. 1800 - 1700 Ma
Delhi belt + Aravalli belt
Norite
Deformation of cover and basement (including granulites)
c. 1700 - 1500 Ma
Erinpura Granite
Tectonic excavation or obduction of granulites
Shear zone
Welding of mantle lithosphere
c. 1500 - 900 Ma

**Fig.3A-32.** Ensialic orogenic model after Sharma (1995).

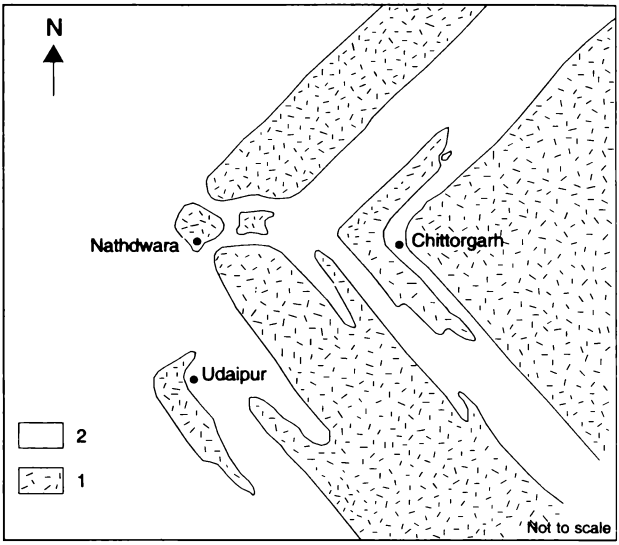


**Fig.3A-33.** Basin inversion model of Aravalli basin (after Roy and Jakhar, 2002, p.120). 1 - Landmass of basement rocks. 2 - Supracrustal basins.

was attributed to the later Delhi orogeny. Sandmata Complex and Mangalwar Complex were 'pop up' structures exhumed from depth along shear zones. Aravalli orogeny ended at 1850 Ma. NDFB evolved in rifts, graben and aulacogens as four isolated basins on a passive continental margin viz. Bayana, Lalsot, Alwar and Main Delhi Belt. There are no calc-alkaline sequences or effects of compression to favour subduction. The basins were closed by inversion, granite intrusion and regional metamorphism at 1450 Ma.

Sinha-Roy (2000) described the Aravalli belt as an aulacogen that widened southwards from a triple junction near Nathdwara (Fig.3A-34). A major strike-slip fault emanating from triple junction opened as SDFB in Mesoproterozoic. Another strike-slip fault propagating from Aravalli aulacogen near Salumbar splayed into multiple strike-slip faults to form pull-apart basins hosting Pb-Zn mineralisation (Rajpura-Dariba, Pur-Banera etc). The Aravalli sediments and volcanics were underthrust to the east, and intruded by Rikhabdev ophiolite. Synkinematic granites (Darwal, Amet and Anjana) were emplaced around 1800 Ma. The Aravalli orogeny was followed soon by the Delhi orogeny (Fig.3A-34). Delhi fold belt has two components: (1) NDFB evolved as fault-bound graben and half-graben as part of aborted rift related to Sambar-Dausa fault. The sediments were intruded by Bairat granite at 1650 Ma. (2) SDFB is a linear belt formed as a transtensional rift that opened into a sea like the Red Sea. The eastern continental platform sediments (Bhim and Rajgarh Groups) were in tectonic contact with the western volcanic suites of Barotiya and Sendra Groups consisting of basalt-andesite-rhyolite (island arc suite). Ranakpur

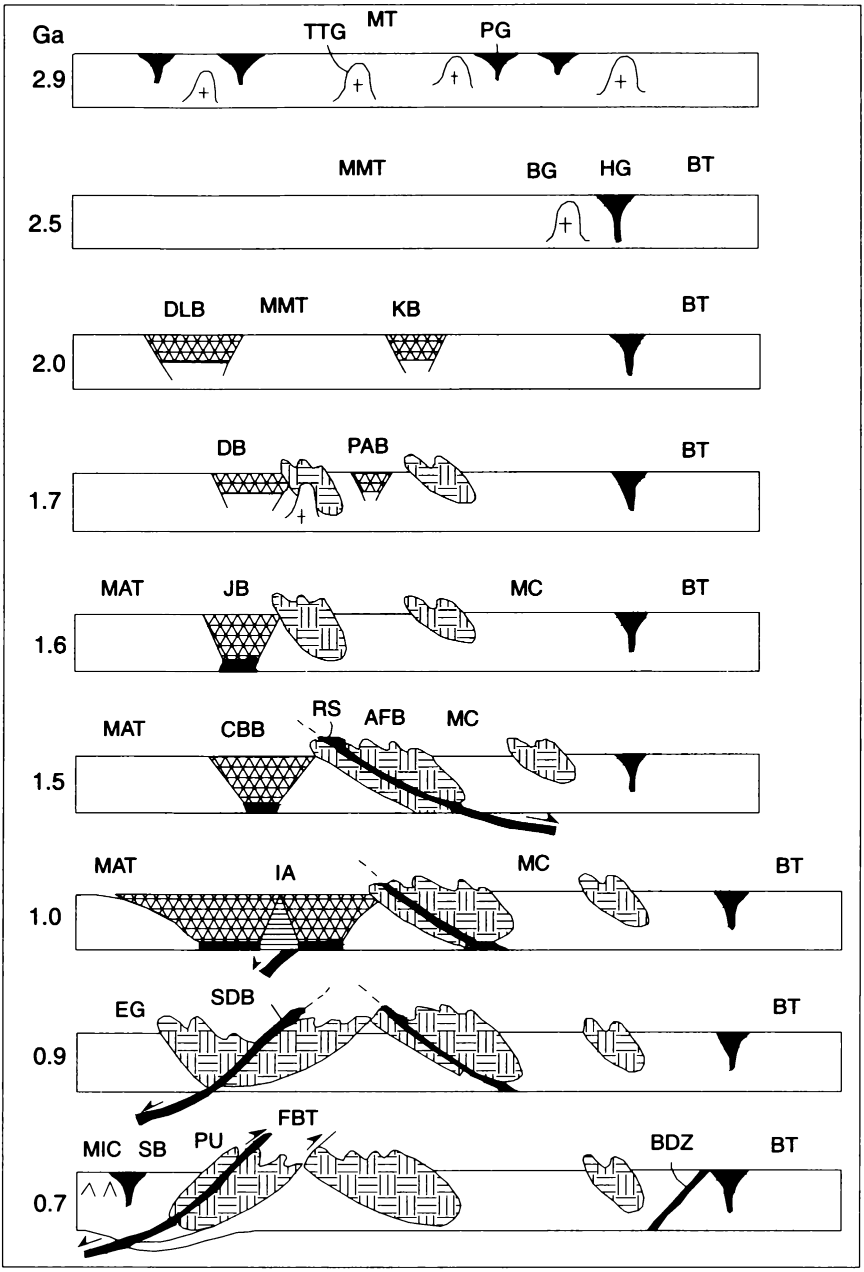

Ga
TTG
MT
PG
2.9
MMT
BG
HG
BT
2.5
DLB
MMT
KB
BT
2.0
DB
PAB
BT
1.7
MAT
JB
MC
BT
1.6
MAT
CBB
RS
AFB
MC
1.5
MAT
IA
MC
BT
1.0
EG
SDB
BT
0.9
FBT
MIC
SB
PU
BDZ
BT
0.7

**Fig.3A.34.** Cartoon showing the development of fold belts in Aravalli craton (Sinha-Roy, 2000). TTG - Tonalite-trondhjemite-granodiorite suite; PG - Primary greenstones; MMT - Mewar-Marwar Terrains; BG - Berach granite; HG - Hindoli Group; BT - Bundelkhand Terrain; DLB - Delwara basin; DB - Debari basin; KB - Khetri basin; PAB - Pull apart basin; JB - Jharol basin; MC - Mangalwar Complex; MT -Mewar Terrain; MAT - Marwar Terrain; CBB - Bhim basin; RS - Rikhabdev suture; AFB - Aravalli fold belt; IA - Island arc; EG - Erinpura granite; SDB - South Delhi fold belt; PU - Phulad ophiolite; MIC - Malani Igneous Suite; SB - Sirohi basin; FBT - Fold belt terrain; BDZ - Banas lineament.

gabbros dated at 1000-1100 Ma intruded the sequence. The marginal sea sequence of Phulad ophiolite was emplaced at 990 Ma. Sendra-Ambaji and Erinpura granites (900 Ma) formed due to westward thrusting of Delhi oceanic crust.

## Neoproterozoic of Marwar Craton

The essentially anorogenic development of Marwar craton marked by the evolution of post-orogenic basins (Sirohi, Sindreth and Punagarh) of Delhi orogeny, emplacement of MIS, and culmination with the development of Marwar evaporite basins by the terminal Proterozoic has been discussed under the section on MIS and therefore is not repeated here.

## SUMMARY OF STRATIGRAPHIC COLUMN

A generalised tectono-stratigraphic table is given below to summarise the evolution of Aravalli craton from Mesoarchaean to Neoproterozoic.

| | |
|---|---|
| Neoproterozoic<br>(500-550 Ma) | Marwar Supergroup |
| (720-750 Ma) | Malani Igneous Suite |
| (800-850 Ma) | Sindreth/Punagarh Groups<br>Sirohi Group |
| (900 Ma) | Erinpura Granite |
| Mesoproterozoic<br>(1100-900 Ma) | Delhi Supergroup<br>South Delhi Fold Belt |
| (1600-1450 Ma) | North Delhi Fold Belt |
| Palaeoproterozoic<br>(1800-1700 Ma) | Hindoli Group<br>Sandmata Complex |
| (2200-1800 Ma) | Aravalli Supergroup & Mineralised Basins (Rajpura-Dariba etc.) |
| Neoarchaean<br>(2900-2600 Ma) | Mangalwar Complex with Bhilwara Group |
| Mesoarchaean<br>(3300-3000 Ma) | Mewar Gneiss with Jagat Group |

The complex geology of Aravalli craton involving many orogenic cycles and cratonisation events needs to be constrained better by multiple isotopic dating methods applied to areas with adequate ground truth.

# 4

# Mobile Belts

## EASTERN GHATS MOBILE BELT

### INTRODUCTION

The Proterozoic Eastern Ghats Mobile Belt (EGMB) extends for about 1000 km in a NE direction from Ongole in Andhra Pradesh in the south to Brahmani River in Orissa in the north, with a maximum width of about 300 km, tapering from north to south (Fig.4E-1). The mobile belt occurs along the eastern margin of Deccan Protocontinent consisting of the Archaean Dharwar, Bastar and Singhbhum cratons. It is overlain by Phanerozoic sediments along the East Coast and is bordered by the Bay of Bengal. The belt is dissected by two prominent grabens of Mahanadi and Godavari. The belt derives its name from the mountains of Eastern Ghats in the East Coast of India. Geographically the term Eastern Ghats includes the Nallamalai Hills of Cuddapah basin and the charnockite massifs of Southern Granulite Terrain, but geologically it is restricted to the mountain belt close to the East Coast and is essentially a granulite belt. It is also referred to as the Eastern Ghats Granulite Belt.

The geological importance of the mobile belt lies in the assembly of Rodinia supercontinent in which EGMB forms part of the SWEAT orogen (Southwest United States and East Antarctica). EGMB is separated from Antarctica during the break up of Gondwana supercontinent. The belt is also well known for UHT (ultrahigh temperature) metamorphism of ~1000°C at 9-10 kbar corresponding to lower crustal depths of 30 to 35 km. Granulite facies rocks such as charnockites, khondalites and leptynites dominate the belt. Nepheline syenites occur near the western and northern margins, layered anorthosite in the south and massif anorthosite in the north. EGMB is well known for its vast resources of bauxite and small deposits of manganese, graphite, sillimanite and gemstones. The belt is the main provenance for thorium and titanium rich beach placers along the East Coast of India.

## Previous Studies

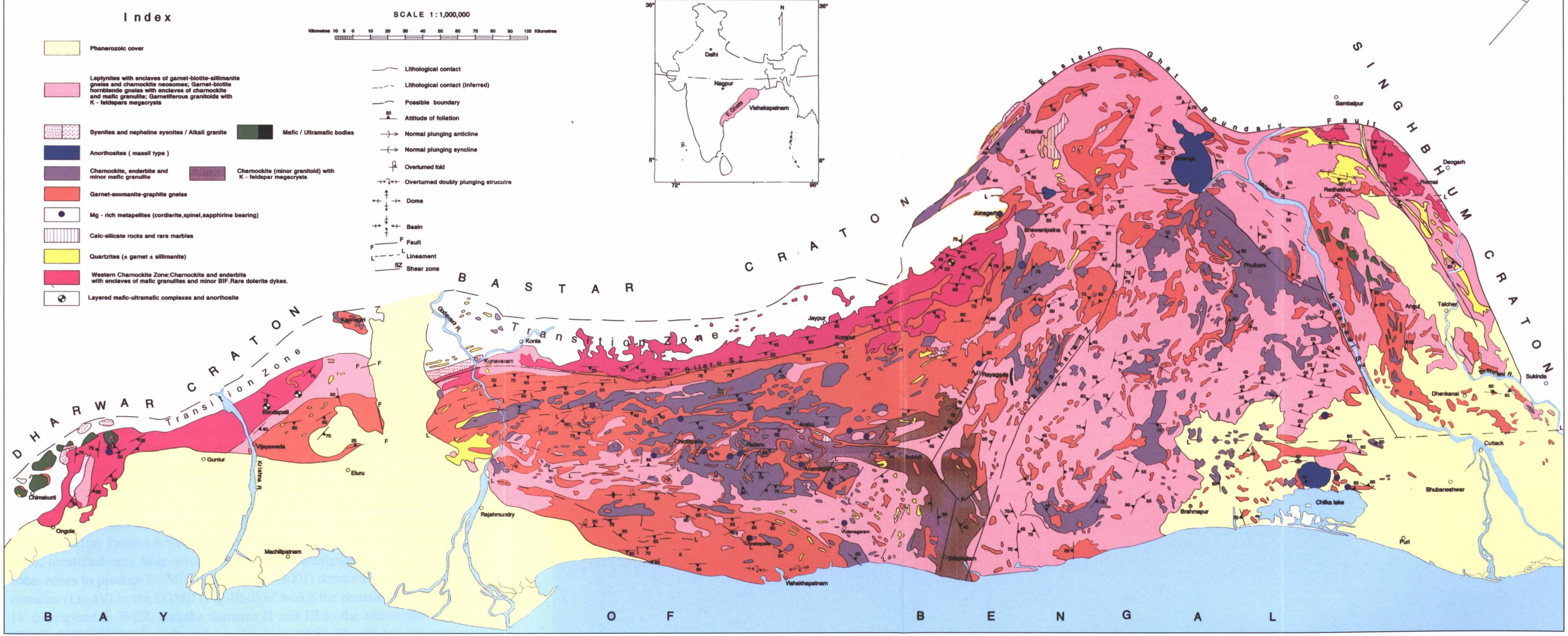
The early pioneers in the study of EGMB are V.Ball, C.S. Middlemiss, T.L.Walker, L.L. Fermor and H. Crookshank. Walker (1902) named the ubiquitous rock type of garnet-sillimanite-graphite gneiss as khondalite after the Khond tribes of the region. E.Wenk called the similar gneiss from the Alps Mountains of Europe as stronalite. Fermor (1936), who classified the ancient rocks of India into Charnockite Province and Non-Charnockite Province, included the EGMB in the Charnockite Province. Crookshank (1938) studied the western boundary of EGMB near Jeypur (Jeypore ) in Orissa and described it as irregular due to the intrusion of charnockite that sent apophyses into the gneisses. He refuted the earlier view of faulted margin along which the 'katazonal' charnockite was uplifted and exposed to form the present topography.

Geological mapping of the EGMB is handicapped by the thick weathered crust, limited accessibility, dense vegetation, lack of marker horizons and the absence of unconformities. Isotopic age data have started pouring in, but the inter-relation among the rock units is still not fully resolved (Rickers et al. 2001). Geological Survey of India (GSI) completed the geological mapping of EGMB on 1:63360/50000 scale in the early nineties and provided periodic syntheses of regional geology, e.g, Murthy et al. (1971), Narayanaswami (1975) and Banerji (1990). Other reviews include those by Bose (1979) and S. Bhattacharya (1996, 2004). Recently, a new 1:1000000 scale map of EGMB has been compiled and regional geology summarized by Ramakrishnan et al. (1998). The details of various early stratigraphic schemes proposed for EGMB are provided in Ramakrishnan et al. (1998) and are not included here. Structural studies are limited to small areas around Angul, Chilka Lake, Salur, Visakhapatnam and the northwestern margin. Metamorphic P-T-t paths and petrological evolution of EGMB are summarised by Dasgupta and Sengupta (2000, 2003). Reviews of alkaline magmatism (Ratnakar and Leelanandam, 1989; Leelanandam, 1993; Mazumder et al. 2000) and anorthosite plutonism (Leelanandam, 1990; Joshi et al. 2004) describe the magmatic evolution of EGMB. Dasgupta and Sengupta (2000), Rickers et al. (2001), Sarkar and Paul (1998) and Dobmeier and Raith (2003) have reviewed geochrological data of EGMB. Comprehensive overviews of EGMB are available in Ramakrishnan et al. (1998), Dobmeier and Raith (2003), Gupta (2004), Nanda (2008), Vijaya Kumar and Leelanandam (2008) and Mukhopadhyay and Basak (2009).

The early stratigraphic classifications divided the EGMB into three major series/groups/suites, namely, charnockites, khondalites and migmatites.

Fig.4E-1.

# GEOLOGICAL MAP OF EASTERN GHATS MOBILE BELT


Index
Phanerozoic cover
Leptynites with enclaves of garnet-biotite-sillimanite gneiss and charnockite neosomes; Garnet-biotite hornblende gneiss with enclaves of charnockite and mafic granulite; Garnetiferous granitoids with K - feldspars megacrysts
Syenites and nepheline syenites / Alkali granite
Mafic / Ultramafic bodies
Anorthosites ( massif type )
Charnockite, enderbite and minor mafic granulite
Charnockite (minor granitoid) with K - feldspar megacrysts
Garnet-sillimanite-graphite gneiss
Mg - rich metapelites (cordierite,spinel,sapphirine bearing)
Calc-silicate rocks and rare marbles
Quartzites (± garnet ± sillimanite)
Western Charnockite Zone:Charnockite and enderbite with enclaves of mafic granulites and minor BIF.Rare dolerite dykes.
Layered mafic-ultramafic complexes and anorthosite
SCALE 1:1,000,000
Kilometres 10 5 0 10 20 30 40 50 60 70 80 90 100 Kilometres
Lithological contact
Lithological contact (inferred)
Possible boundary
50
Attitude of foliation
Normal plunging anticline
Normal plunging syncline
Overturned fold
Overturned doubly plunging strucutre
Dome
Basin
F
F Fault
L
L Lineament
SZ Shear zone
36° 72° 96° 36°
N
Delhi
Nagpur
E. Ghats
Vishakapatnam
8° 8°
72° 96°
N
DHARWAR CRATON
Transition Zone
BASTAR CRATON
Transition Zone
Eastern Ghat Boundary Fault
SINGHBHUM CRATON
BAY OF BENGAL
Kannegiri
Godavari R.
Konta
Kunavaram
Kondapalli
Vijayawada
Guntur
Krishna R.
Eluru
Chimakurti
Ongole
Machilipatnam
Rajahmundry
Sileru SZ
Jaypur
Koraput
Chintapalle
Paderu
Araku
Anantagiri
Vishakhapatnam
Vizianagaram
Bobbili
Srikakulam
Rayagada
Nagavalli SZ
Vamsadhara SZ
Khariar
Junagarh
Bhawanipatna
Bolangir
Phulbani
Mahanadi R.
Mahanadi SZ
Sambalpur
Deogarh
Redhakhol
Riamal
Angul
Talcher
Brahmani R.
Sukinda
Dhenkanal
Cuttack
Bhubaneshwar
Chilka lake
Puri
Brahmapur

Charnockites and khondalites mutually occupied the lower or upper position in different classifications, depending on individual preferences. Migmatitic gneisses were, however, given the uppermost position among the three units in all classifications. There are also problems of terminology. Modern metamorphic petrology accepts only the rock nomenclature (e.g. schist, gneiss) with mineralogical prefix (e.g. garnet-sillimanite gneiss, cordierite-garnet gneiss etc) and so the rock term khondalite may not be in order (Banerji, 1982a), but the tradition of long usage still persists. Khondalite is also used in the stratigraphic sense to include the garnet-sillimanite-graphite gneisses, Mg-Al metapelites, quartzites, marbles, calc-silicate rocks and manganese formations. A compromise solution may be to continue the use of khondalite as a rock name using small letter 'k' and Khondalite Group with capital letters as stratigraphic name, as prescribed in the stratigraphic codes. Similarly, charnockite may be used as a term for deep-seated metamorphic equivalents of granitoids such as charnockite, charno-enderbite, enderbite etc. Since charnockite does not have a well-defined stratigraphic position because of its derivation from granitoids and leptynites of different ages, it is not used here as a stratigraphic unit. Another common rock type of EGMB is leptynite, which is a garnetiferous quatzofelspathic leucogneiss. The non-garnetiferous equivalent of leptynite is leptite, but this term is not in common use. Most of the gneisses that have palaeosomes of either orthogneiss (hornblende or biotite gneiss) or para-gneiss (khondalite, Mg-Al pelite, garnetiferous gneiss), charnockites or metabasic rocks and neosomes of quartzofelspathic rock are called migmatites or migmatitic gneisses.

## ZONATION OF EGMB

Ramakrishnan et al. (1998) divided the EGMB into four longitudinal zones (Figs.4E-1;4E-3a) on the basis of dominating rock type or lithological association, expanding the division earlier proposed for the Koraput-Brahmapur (Berhampur) traverse by Nanda and Pati (1989). The designated rock units are, however, not exclusive to individual zones, and the zonal boundaries are only broadly demarcated. The four zones are (i) Western Charnockite Zone (WCZ), (ii) Western Khondalite Zone (WKZ), (iii) Central Migmatite Zone (CMZ) and (iv) Eastern Khondalite Zone (EKZ). Chetty (2001), on the other hand, identified nine large terranes which were amalgamated along curved shear zones to produce EGMB. Rickers et al. (2001) demarcated four isotopic domains (I to IV) in the EGMB (Fig.4E-2) of which the domains 1A, 1B and IV correspond to WCZ, and the domains II and III to the remaining zones (WKZ, CMZ and EKZ) of Ramakrishnan et al. (1998) (Fig.4E-3a). The main difference in the scheme of Rickers et al. (2001) is the separation of domains II

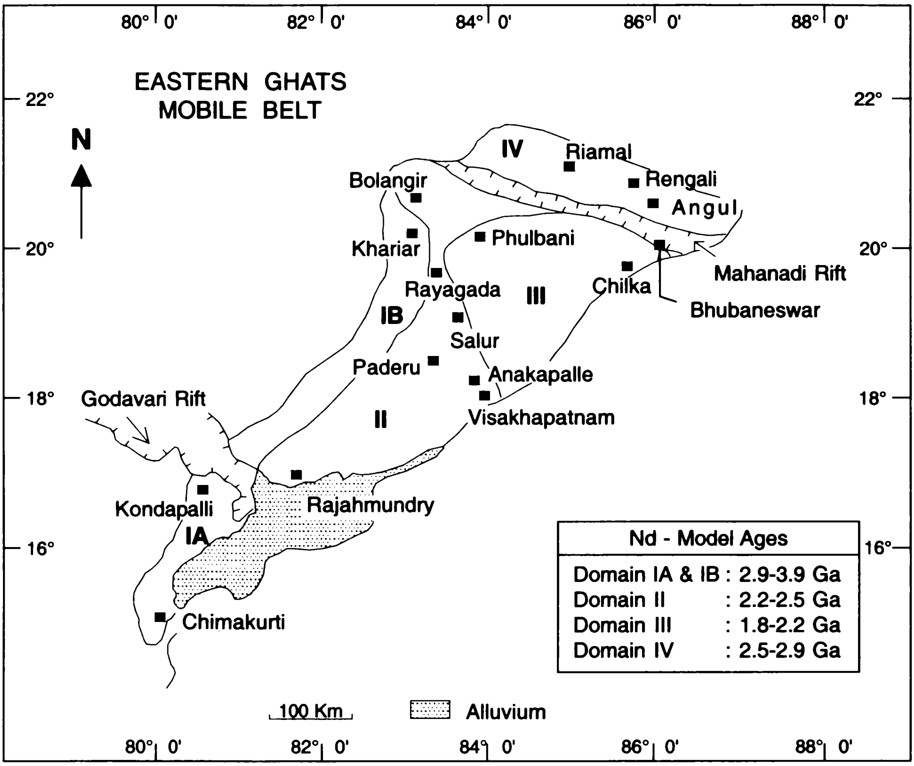

EASTERN GHATS MOBILE BELT
N
80° 0'
82° 0'
84° 0'
86° 0'
88° 0'
22°
20°
18°
16°
IV
Riamal
Rengali
Angul
Bolangir
Khariar
Phulbani
Mahanadi Rift
Chilka
Bhubaneswar
Rayagada
III
IB
Salur
Paderu
Anakapalle
Godavari Rift
II
Visakhapatnam
Kondapalli
Rajahmundry
IA
Chimakurti
Nd - Model Ages
Domain IA & IB : 2.9-3.9 Ga
Domain II : 2.2-2.5 Ga
Domain III : 1.8-2.2 Ga
Domain IV : 2.5-2.9 Ga
100 Km
Alluvium

**Fig.4E-2.** Distribution of different isotopic domains (modified from Dasgupta and Sengupta, 2003) in the Eastern Ghats mobile belt.

and III by Nagavalli-Vamsadhara shear zone. Recent synthesis of isotopic data and new geological information from different sectors have led Dobmeier and Raith (2003) to divide EGMB into four provinces (Fig.4E-3b), namely Krishna province, Jeypore (Jeypur) province, Rengali province and Eastern Ghats province. The former three provinces correspond to WCZ, whereas the Eastern Ghats province covered the remaining zones of WKZ, CMZ and EMZ. Significantly, the subdivision by Dobmeier and Raith (2003) does not include the Nagavalli-Vamsadhara shear zone as a province boundary that was adopted by Rickers et al. (2001) based on isotopic mapping. The various divisions under different schemes are shown in Table 4E-1 for comparison. The division proposed by Ramakrishnan et al. (1998) will be followed here, but mention will be made of the other divisions where appropriate. Dobmeir and Raith (2003) is followed by many authors (Mukhopadhyay, 2009).

## MARGINAL OR TRANSITION ZONE

A wide marginal or transition zone or an orogenic 'front' marks the contact between EGMB on the one hand and the three cratons of Deccan Protocontinent

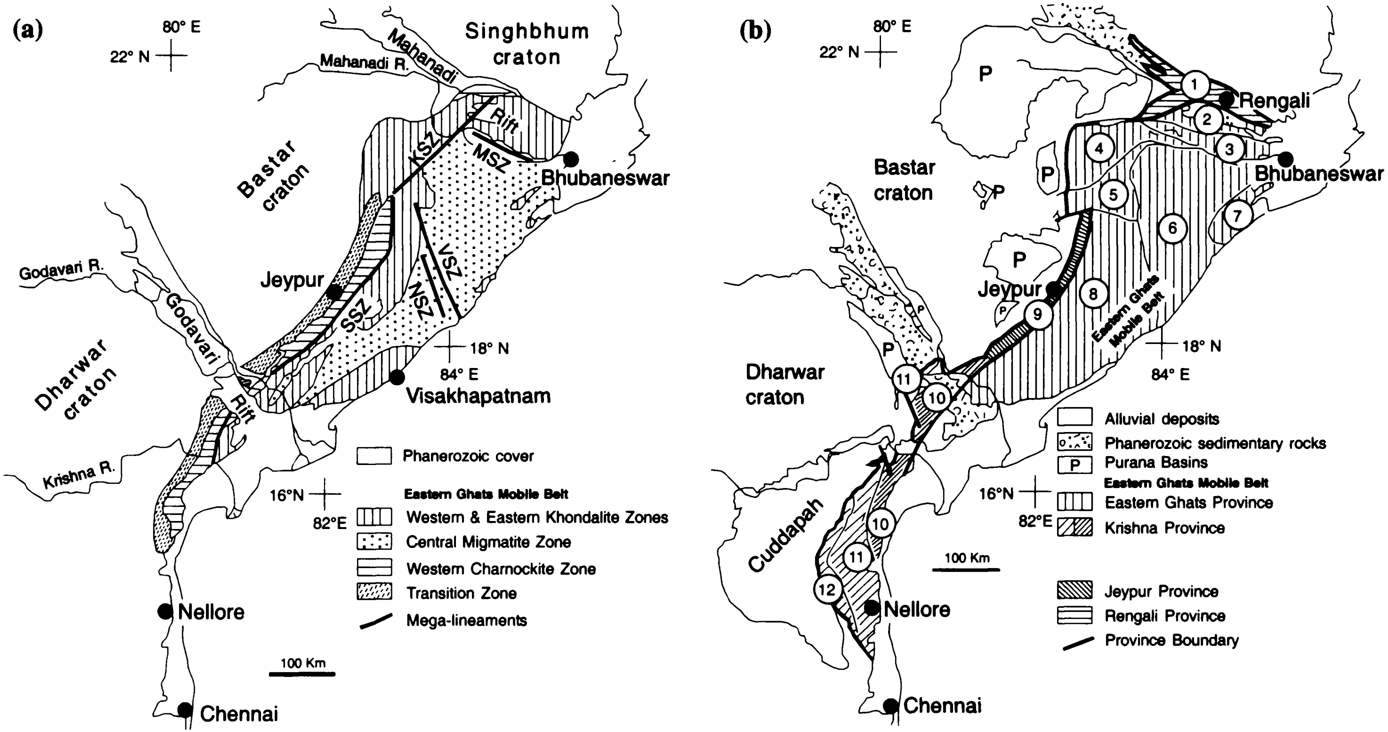

(a)
80° E
22° N
Singhbhum craton
Mahanadi R.
Mahanadi
Rift
KSZ
MSZ
Bhubaneswar
Bastar craton
Godavari R.
Jeypur
SSZ
NSZ
VSZ
Godavari
Dharwar craton
Rift
18° N
84° E
Visakhapatnam
Krishna R.
16°N
82°E
Nellore
Chennai
100 Km
Phanerozoic cover
Eastern Ghats Mobile Belt
Western & Eastern Khondalite Zones
Central Migmatite Zone
Western Charnockite Zone
Transition Zone
Mega-lineaments
(b)
80° E
22° N
P
1
2
3
4
5
6
7
8
9
10
11
12
Rengali
Bhubaneswar
Bastar craton
Jeypur
Eastern Ghats Mobile Belt
18° N
84° E
Dharwar craton
Cuddapah
16°N
82°E
100 Km
Nellore
Chennai
Alluvial deposits
Phanerozoic sedimentary rocks
Purana Basins
Eastern Ghats Mobile Belt
Eastern Ghats Province
Krishna Province
Jeypur Province
Rengali Province
Province Boundary

**Fig.4E-3.** (**a**) Outline map of tectonic divisions of EGMB (after Ramakrishnan et al. 1998). SSZ - Sileru Shear Zone; KSZ Koraput Shear Zone; MSZ - Mahanadi Shear Zone; NSZ - Nagavalli Shear Zone; VSZ - Vamsadhara Shear Zone. (**b**) Subdivisions of provinces and domains of EGMB (after Dobmeier and Raith, 2003, with permission from Geological Society of London). For provinces see index. Domains: 1 - Rengali; 2 - Angul; 3 - Tikarpara; 4 - Khariar; 5 - Rampur; 6 - Phulbani; 7 - Chilka Lake; 8 - Visakhapatnam; 9 - Jeypur; 10 - Ongole; 11 - Vinjamuru; 12 - Udayagiri.

**Table 4E-1.** Divisions of Eastern Ghats Mobile Belt by different authors

| Ramakrishnan et al.1998 | Rickers et al. 2001 | Dobmeier and Raith, 2003 |
|---|---|---|
| Western Charnockite Zone | Domain IA, IB (2.9-3.9 Ga) and Domain IV (2.5-2.9 Ga) | Krishna Province (including Nellore-Khammam schist belt and Ongole domain) |
| Western Khondalite Zone | Domain II (2.2-2.5 Ga) (south of Nagavalli-Vamsadhara shear zone) | Jeypore Province<br>Rengali Province |
| Central Migmatite Zone | | |
| Eastern Khondalite Zone | Domain III (1.8-2.2 Ga) (north of Nagavalli-Vamsadhara shear zone; no Archaean imprint) | Eastern Ghats Province |

N.B. Dobmeier and Raith (2003) subdivided the provinces into domains separated by lineaments. Rengali Province includes only the Rengali domain; Jeypore Province includes only the Jeypore domain; Eastern Ghats Province includes Angul, Tikarpara, Khairar, Rampur, Phulbhani, Chilka Lake and Visakhapatnam domains; Krishna Province includes Ongole, Vinjamuru and Udayagiri domains.

on the other. In Dharwar and Bastar cratons, the marginal zone begins at the faulted eastern margins of Proterozoic platform ("Purana") basins of Cuddapah, Pakhal, Sabari, Indravati, Ampani, Khariar and Chhattisgarh. The marginal zone also includes the WCZ, the eastern boundary of which is the Sileru Shear Zone. The zones occurring to the east of Sileru Shear Zone (namely, WKZ, CMZ and EKZ) constitute the Eastern Ghat mobile belt *sensu stricto.* The transition zone of EGMB with the different cratons, from south to north, is described below.

### Contact with Dharwar Craton

The transition zone begins near the Cuddapah boundary thrust in the north, and passing through the western margin of Nellore schist belt, disappears under the Phanerozoic sediments close to Pulicat Lake that is situated to the north of Chennai. The zone extends along the Sharnavala outlier of Pakhal basin, but further north near Khammam, the contact becomes sharply discordant, with its NE trend abutting against the NW trends of the Archaean high-grade enclaves (Warangal Group), together with the closely associated Archaean Karimnagar granulite belt.

Kannegiri granulite massif abruptly rises from the plains (Sarvothaman et al. 1999) within the marginal zone between Sharnavala outlier and EGMB near Vijayawada. Charnockites with mafic granulite bands, leptynites and khondalites are closely associated in Kannegiri hill (Fig.4E-4). Incipient

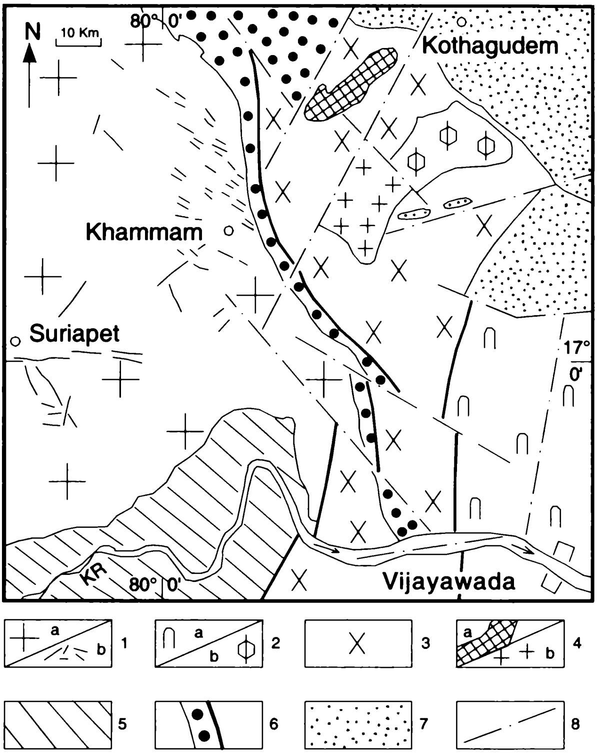


**Fig.4E-4.** Geology of Kannegiri area (after Sarvothaman et al. 1999, p.136). 1a - Eastern Dharwar craton; 1b - Major dykes; 2a - EGMB; 2b - Kannegiri granulite; 3 - Marginal zone of EGMB; 4a - Chimalpahad anorthosite; 4b - Khammam schist belt; 5 - Cuddapah basin (northern part); 6 - Sharnavala outlier of Pakhal basin; 7 - Godavari basin; 8 - Faults.

charnockitization is noticed in the marginal zone. The isolated Kannegiri granulite outcrop may be similar to the klippen of Himalaya as well as Katargama klippe of Sri Lanka. Similar klippes are seen near Khariar in the north. A small body of carbonatite, probably related to the Kunavaram nepheline syenite, is seen in Kannegiri hill.

### Nellore-Khammam Schist Belt

Nellore-Khammam schist belt (NKSB) is the largest schist belt (Fig.4E-5) of Eastern Dharwar craton (EDC) and occurs within the marginal zone of the EGMB. It is distinctly different from the other schist belts of EDC in that:

(a) It has rock types similar to those of the Western rather than Eastern Dharwar craton.

(b) The metamorphism of NKSB is medium pressure kyanite-sillimanite type as opposed to the andalusite-sillimanite type in EDC.

(c) The overall structural trend of NKSB is concave to the east and parallel to that of EGMB rather than that of the schist belts of EDC, which are convex eastward. Had its original trend before the Eastern Ghats orogeny been parallel to that of schist belts of EDC, portions of the belt should have emerged from beneath the Cuddapah basin between Warangal and Hyderabad, but this is not the case.

(d) NKSB emerges abruptly as a large schist belt in the easterly direction towards which the Eastern greenstone belts progressively narrow down in width (e.g., Ramagiri to Pedddavuru and Tsundupalle) due to pre-Cuddapah denudation. This implies that Nellore schist belt was not present when the Archaean Eastern greenstone belts were developed.

(e) NKSB transects the trends of greenstone belts and the parallel Warangal Group enclaves of EDC in the east of Khammam, suggesting a younger age for NKSB.

(f) NKSB does not extend prominently into Bastar craton, and therefore its development is perhaps limited to Dharwar craton. The belt has structural trends parallel to that of EGMB and the Nallamalai fold belt of Cuddapah basin. Since the 'Purana' basins and EGMB extend across the Dharwar and Bastar cratons, and NKSB is restricted to Dharwar craton, its evolution is earlier than that of EGMB (>1500 Ma) and Nallamalai fold belt (>1600 Ma), but later than that of Dharwar belts (<2500Ma), and most probably around 2200-1800 Ma.

*Nellore schist belt*: This belt (Fig.4E-5) extending for about 200 km from Sulurpeta to Podili is divided into Udayagiri domain in the west and Vinjamuru domain in the east. Udayagiri domain is predominantly sedimentary with local volcanic intercalations. Cross-bedded quartzites and quartz-mica schists are associated with chlorite-sericite-quartz schists, with local quartz pebble conglomerate. Anthophyllite schists, felsic volcanics and volcanic breccias are seen at places. Amygdular metabasalt is also found locally. In Vinjamuru domain, amygdular and pillowed amphibolites are metamorphosed to migmatitic hornblende gneisses. Conformable bands of felsic volcanics are also seen. Recrystallized quartzites, rarely preserving cross bedding, are intercalated with amphibolites and pelitic schists. Pelitic schists are rich in garnet, staurolite, kyanite and sillimanite. Impersistent BIF bands associated with felsic mafic volcanics are also noticed. Pelitic schists near Vinjamuru are closely inter-layered with crystalline limestone (earlier mistaken for carbonatite), felsic agglomerate, tuff and porphyry, banded barite-magnetite rock, cordierite-anthophyllite rock and quartz-hematite-sericite schist. A small circular massif-type anorthosite of *Inukurti* intrudes the Vinjamuru domain (Narsimha Reddy et al. 2003).

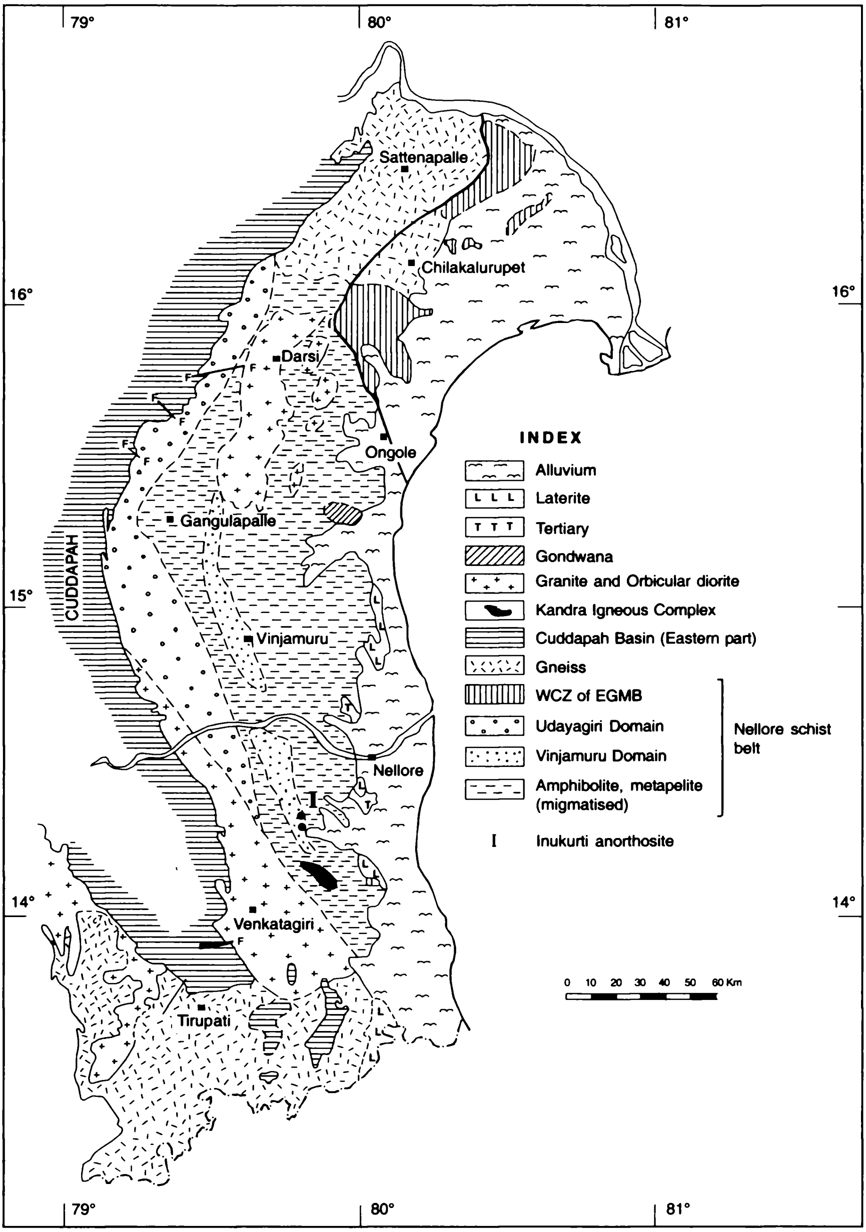

79°
80°
81°
16°
15°
14°
Sattenapalle
Chilakalurupet
Darsi
F
Ongole
Gangulapalle
CUDDAPAH
Vinjamuru
Nellore
I
Venkatagiri
Tirupati
L
T
INDEX
Alluvium
Laterite
Tertiary
Gondwana
Granite and Orbicular diorite
Kandra Igneous Complex
Cuddapah Basin (Eastern part)
Gneiss
WCZ of EGMB
Udayagiri Domain
Vinjamuru Domain
Amphibolite, metapelite (migmatised)
Nellore schist belt
I Inukurti anorthosite
0 10 20 30 40 50 60Km

**Fig.4E-5.** Geology of Nellore schist belt (after Ramam and Murty, 1997).

Udayagiri domain was earlier correlated with the Dharwar sequence, and Vinjamuru domain with the Sargur sequence, separated possibly by a fault (Vasudevan and Rao, 1976). The low grade Udayagiri domain was therefore believed to be younger than the high grade Vinjamuru domain. Such a distinction becomes untenable in the light of recent studies, and the entire sequence represents one progressive metamorphic unit from west to east.

All the rocks of Nellore belt are folded into tight isoclinal folds in two phases followed by later open folds. The metamorphism is of medium pressure Barrovian (kyanite-sillimanite) type, in the range of 700–750°C at 7-8 kbar. The age of Nellore schist belt is constrained by single zircon Pb-Pb evaporation date of felsic volcanics at 1868±6 Ma and 1771±8 Ma. An older Rb-Sr WR age of 2201±142 (with large error) and a younger age of 1534±14 Ma are reported. Many dates obtained in the past converge at 1500-1600 Ma, with metamorphic overprint or cooling ages of 1100, 550-600 and 500 Ma.

*Kandra Igneous complex:* This was earlier known as Kandra Volcanics covering 40 km x 4 km area, and is seen near Kandra in Nellore schist belt. It consists of a series of basic sills, dykes and flows (now amphibolites) associated with cumulate leucogabbros, mafic gabbros and minor ultramafics. The metavolcanics show amygdular and pillow structures, and are locally spilitic. Chert bands (now quartzites) are seen locally. This igneous suite is interpreted as an ophiolite (Leelanandam, 1990a; Sesha Sai, 2009). Precambrian ophiolites have incomplete and imperfect preservation and the Kandra ophiolite is no exception (Nagaraja Rao et al. 1991). Similarly near Kanigiri, also in Nellore belt, a chaotic assemblage of pillowed basalts, ultramafics and laminated cherts is found, which is interpreted as an ophiolite melange.

*Khammam schist belt:* This belt extends from southeast of Khammam up to Kothagudem near the Godavari Gondwana basin. Granites and gneisses separate the Nellore and Khammam schist belts, but outcrops are scarce in the Krishna river alluvium, and both belts may therefore be interlinked. The lithological units of Khammam belt are identical to the Vinjamuru domain of Nellore belt with pelitic and psammitic sediments, calc-silicate rocks and BIF. These rocks are intensely migmatised in the east. Khammam belt is syntectonically intruded by the *Chimalpahad* layered anorthosite-gabbro complex (Fig.4E-6a), which is the largest in India covering an area of 200 sq. km (Leelanandam and Narsimha Reddy, 1985). Leucogabbro is the principal rock followed by gabbro and anorthosite. Anorthosite shows typical zebra banding (Fig.4E-6b). Subordinate amounts of ultramafics like pyroxenite, websterite and dunite are seen in the gabbros. Chromitite seams are associated with pyroxenites. Kyanite-corundum rocks are seen at the contact of pegmatites intruding the ultramafics. The parental magmas of the complex are considered to be aluminous tholeiites involved in low-pressure fractionation. About seven satellite intrusions of gabbro-anorthosite, as at Jannaram, Tallada and Ligannapeta are seen around the main body. Farther south of the complex, occurs the small body of *Sripuram* anorthosite.

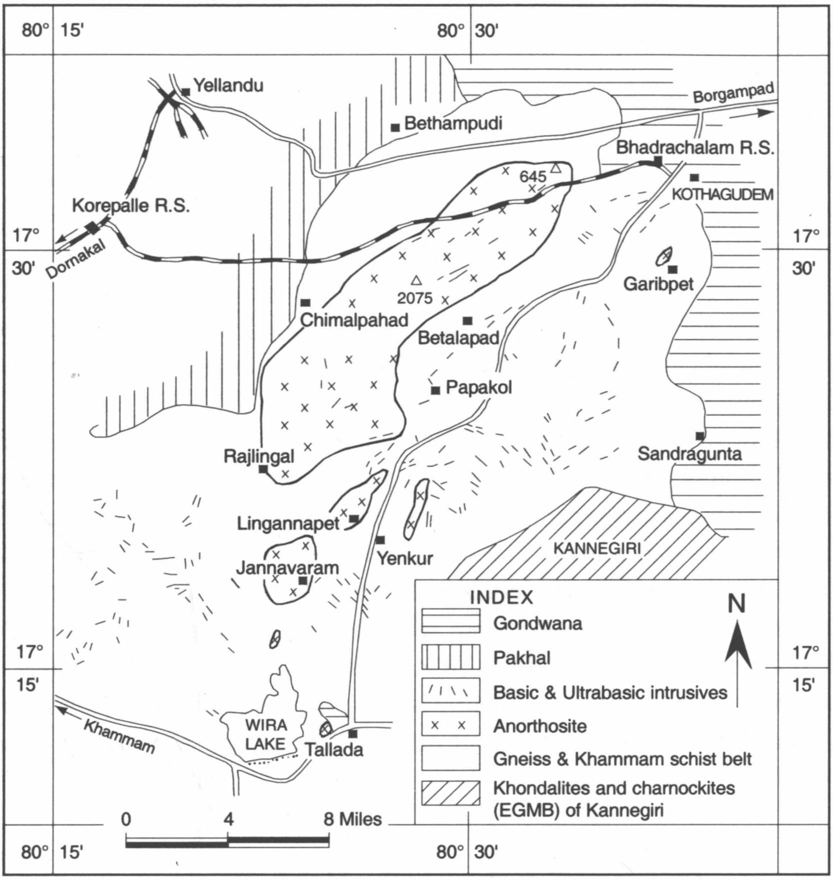

80° 15'
80° 30'
Yellandu
Borgampad
Bethampudi
Bhadrachalam R.S.
645
KOTHAGUDEM
Korepalle R.S.
17° 30'
Dornakal
Garibpet
2075
Chimalpahad
Betalapad
Papakol
Rajlingal
Sandragunta
Lingannapet
Yenkur
KANNEGIRI
Jannavaram
INDEX
Gondwana
Pakhal
Basic & Ultrabasic intrusives
Anorthosite
Gneiss & Khammam schist belt
Khondalites and charnockites (EGMB) of Kannegiri
N
17° 15'
Khammam
WIRA LAKE
Tallada
0
4
8 Miles

**Fig.4E-.6a.** Geological setting of Chimalpahad anorthosite (after Appavadhanulu et al. 1976).

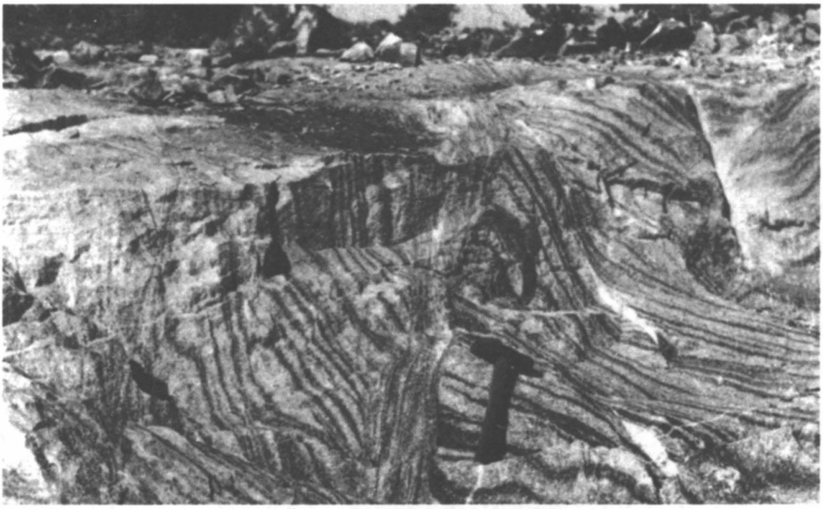


**Fig.4E-6b.** Zebra banding in anorthosite of Chimalpahad complex (Courtesy: C Leelanandam).

### Prakasam Alkaline Province

The transition zone between the Cuddapah boundary thrust and EGMB near Ongole consists of orthogneisses intruded by a series of alkaline plutons (about 14 in number) that belong to Prakasam alkaline province (Leelanandam, 1989). Important among them (Fig.4E-7a) are those of *Elchuru, Purimetla, Uppalapadu, Settupalle* and *Podili* (Ratnakar and Leelanandam, 1989).

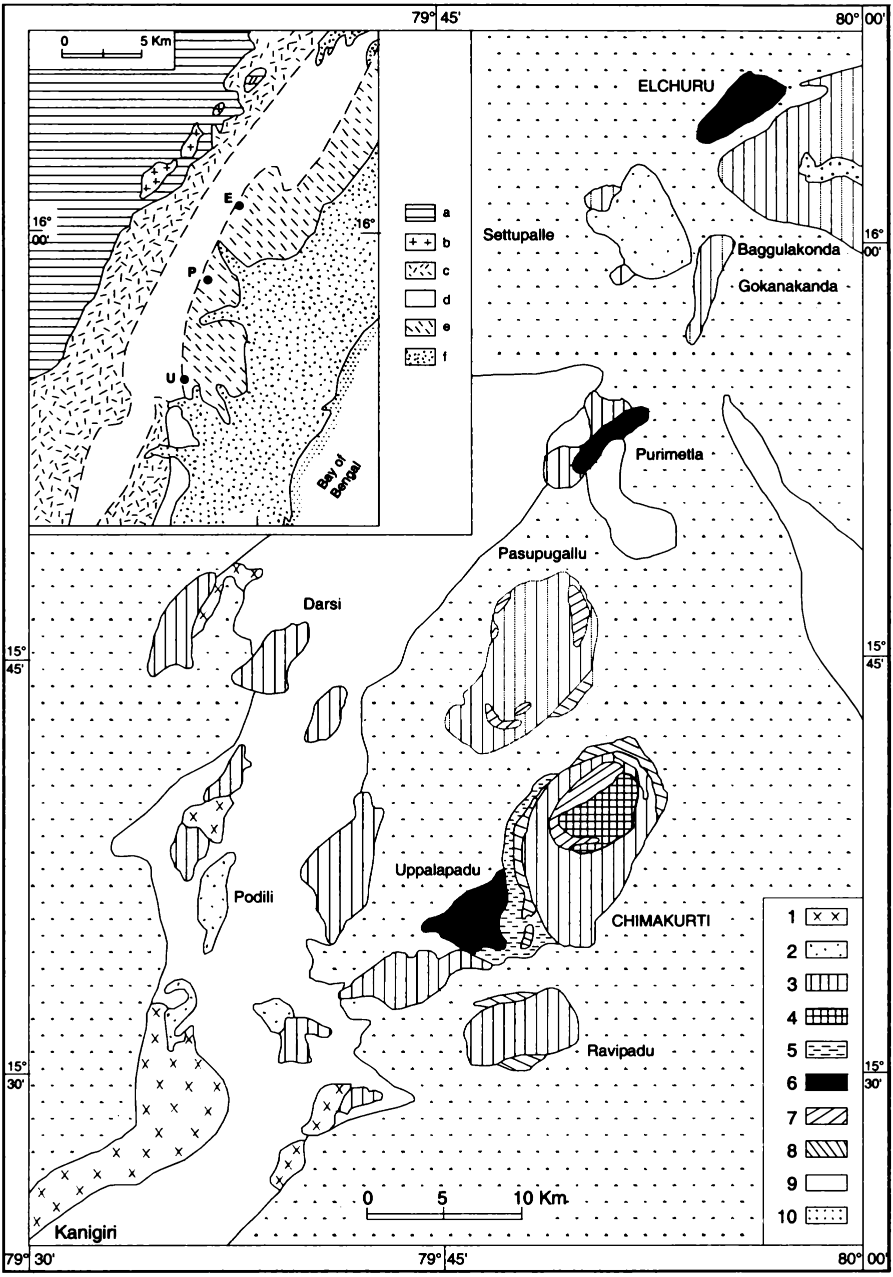
Most of the alkali plutons are rich in nepheline syenite with minor syenite, quartz syenite and alkali granite. They are typically miaskitic plutons and contain essentially nepheline, perthite, albite and quartz. Common mafic minerals are alkali amphiboles (barkevikite, ferrohastingsite and riebeckite) and Fe-rich biotite. Mafic to ultramafic alkaline rocks like melteigite, malignite, shonkinite etc. and lamprophyres occur in minor amounts in the undersaturated plutons. Nepheline syenites are regarded as the end stage differentiation products of melteigites and malignites. The associated ferrosyenites are derived by crystallization under low $fO_2$ conditions from tholeiite magmas. Therefore two distinct differentiation series are recognised in these alkali plutons. The alkali plutons are dated by Rb-Sr WR method indicating an age range of 1250-1350 Ma (e.g. Elchuru ~1240 Ma, Uppalapadu ~1350 Ma, Purimetla ~1370 Ma). The nepheline syenites are deformed locally into nepheline gneisses (Fig.4E-7b).

## Contact with Bastar and Singhbhum Cratons

The marginal zone in contact with the Bastar craton is rather heterogeneous in different sectors and has been a matter of debate (Fig.4E-1). The situation in different areas is described below.

*Jeypur Area, Bastar Craton:* In the area to the north of the Godavari graben, the Bhopalpatnam granulite belt and the associated high-grade schists of Sukma Group in the Bastar craton have trends athwart the EGMB near Konta. The deflection of the WNW-ESE trend lines of Bastar craton into the NE trends of EGMB commences at the eastern margin of Sabari, Indravati, Ampani and Khariar platform basins. The eastern marginal zones of these basins are deformed and weakly metamorphosed, just as in the case of the Nallamalai fold belt of Cuddapah basin. The WNW-ESE trending Bengpal belt is truncated at the eastern tectonic margin between the Sabari and Indravati basins in the Tulsi Dongar area, where the trends swerve parallel to that of EGMB (*see* Crookshank, 1963).

The contact of WCZ with Bastar craton near Jeypur is gradational. The TTG (tonalite-trondjhemite-granodiorite) gneisses of the craton with their


79° 45'
80° 00'
16° 00'
15° 45'
15° 30'
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0 5 Km
E
P
U
16°
Bay of Bengal
a
b
c
d
e
f
ELCHURU
Settupalle
Baggulakonda
Gokanakanda
Purimetla
Pasupugallu
Darsi
Podili
Uppalapadu
CHIMAKURTI
Ravipadu
Kanigiri
0 5 10 Km
1
2
3
4
5
6
7
8
9
10

**Fig.4E-7a.** Nepheline syenite and syenite plutons of the Prakasam alkaline province (Ratnakar and Leelanadam, 1989). 1 - Hornblende alkali granite/quartz syenite; 2 - Hornblende syenite; 3 - Gabbro; 4 - Olivine clinopyroxenite; 5 - Quartz-aegirine syenite; 6 - Nepheline syenite; 7 - Anorthosite; 8 - Khondalite and charnockite; 9 - Hornblende-biotite gneiss; 10 - Amphibolite and migmatite. *Inset:* a - Part of the Cuddapah basin; b - Granite (intrusive); c - Nellore belt; d - Unclassified gneisses; e - Charnockites and khondalites; f - Phanerozoic. E - Elchuru; P - Purimetla; U - Uppalapadu.

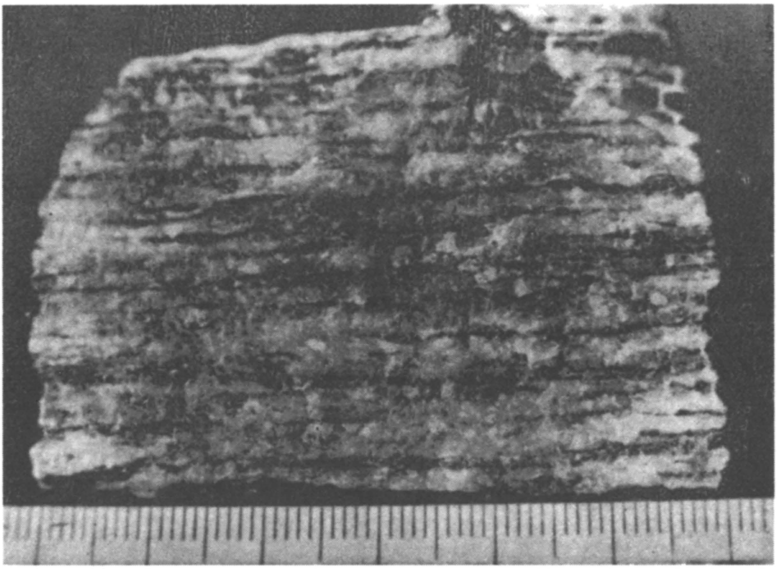
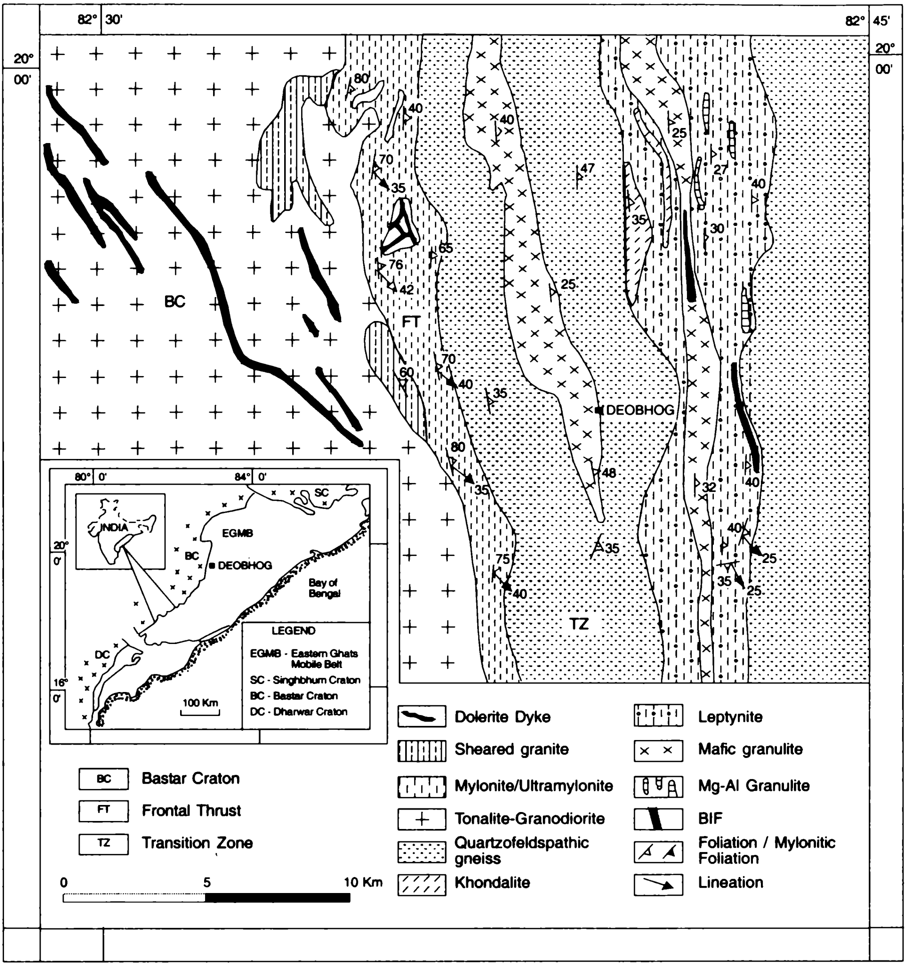


**Fig.4E-7b.** Nepheline syenite gneiss from Elchuru alkaline pluton (from Madhavan et al. 1989, p.198).

amphibolite enclaves show progressive metamorphism towards the charnockites of WCZ near Kolab Power House and Upper Indravati Power House at Mathiguda (Nanda and Pati, 1989). Basic granulite dykes with chilled margins and 'incipient' or 'arrested' charnockite patches are noticed in the marginal zone, similar to that in the Piriyapatna-Hunsur areas of Karnataka in Dharwar craton.

*Khariar Area, Bastar Craton*: In the area between Junagarh (to the west of Bhavanipatna) and Sambalpur, the contact zone has been well studied in Deobhog-Dharamgarh area (Fig 4E-8) and between Khariar and Paikmal. In contrast to the situation in the south, a number of imbricate nappes (Lathore and Turekela nappes after Biswal and Sinha, 2004) mark the contact zone called the Terrane Boundary Shear Zone or TBSZ by Biswal et al. (2004). Later veins of pseudotachylite and carbonate are also reported in the contact zone. Shear sense indicates top-to-NW sense of movement. This contact is described as the Eastern Ghats boundary shear zone in the map of Ramakrishnan et al. (1998) and is regarded as continuation of Sileru shear zone with offset to the west accentuated probably by Nagavalli shear zone. The cratonic rocks near the boundary shear zone are essentially granitoids and gneisses that are cut across by dolerite dykes, which are absent to the east of the thrust zone. The mobile belt rocks are essentially hornblende bearing granitoid gneisses and leptynites containing enclaves of Mg-Al granulites, mafic granulites, BIF, khondalites and calc-granulites, along with superimposed 'patchy' or 'incipient'


82° 30'
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20° 00'
BC
FT
TZ
DEOBHOG
80° 0'
84° 0'
20° 0'
16° 0'
INDIA
SC
EGMB
BC
DEOBHOG
DC
Bay of Bengal
100 Km
LEGEND
EGMB - Eastern Ghats Mobile Belt
SC - Singhbhum Craton
BC - Bastar Craton
DC - Dharwar Craton
BC Bastar Craton
FT Frontal Thrust
TZ Transition Zone
0 5 10 Km
Dolerite Dyke
Sheared granite
Mylonite/Ultramylonite
Tonalite-Granodiorite
Quartzofeldspathic gneiss
Khondalite
Leptynite
Mafic granulite
Mg-Al Granulite
BIF
Foliation / Mylonitic Foliation
Lineation

**Fig.4E-8.** Geology of Deobhog area showing thrust contact of EGMB with Bastar craton (after Neogi and Das, 2000, p.182).

charnockites. Some authors describe the patchy charnockites as xenoliths in leptynite. Some studies suggest that along the west-verging shear zone, the 'hot' charnockites are thrust over the 'cold' gneisses, displaying inverted metamorphism like in Limpopo belt of southern Africa (Gupta et al. 2000; Bhadra et al. 2004), but this is also disputed.

*Northern Boundary with Bastar and Singhbhum Cratons:* Bastar and Singhbhum cratons are separated by the Mahanadi graben and faults bounding it, in the vicinity of Sambalpur (Mahalik, 1994). The contact between EGMB and Singhbhum craton between Sambalpur and Sukinda also gets enmeshed in a series of faults and shear zones (e.g. Sukinda thrust) around the Mahanadi graben. Charnockites of Riamal-Rengali areas form part of WCZ to the north of which the Eastern Ghats boundary shear zone is shown in Fig.4E-1. Large outcrops of sillimanite quartzites associated with metavolcanic amphibolites occur to the south up to Mahanadi graben, which are correlated with the Daitari Group near Deogarh where uraniferous quartz pebble conglomerate occurs (QPC) at the base. Others consider them as equivalent to the Iron Ore Group or Dhanjori Group. The Sukinda and Baula-Nausahi ultramafics (with associated charnockites) containing marginal platinum (PGE or platinum group element) mineralisation are located close to the Sukinda thrust in the Singhbhum craton.

### *Alkaline Complexes*

The craton-mobile belt boundary is characterized by the presence of alkaline rocks in the Bastar and Singhbhum cratons, like those of Prakasam alkaline province occurring in the transition zone of Dharwar craton to the south of Godavari graben. Important among them are the intrusions of Kunavaram, Kunduluru, Borra, Khariar, Bhela-Rajna, Redhakhol (Rairakhol) and Kankrakhol. These alkaline rocks, which occur within gneisses close to the contact with WCZ, are invariably miaskitic in composition, mafic poor and show no perceptible metasomatism of the surrounding rocks. The largest nepheline syenite body at *Kunavaram* (85 km$^2$) consists dominantly of nepheline syenite, hornblende syenite and biotite syenite, with pyroxene syenite at the core. Minor amounts of quartz syenite, melteigite, malignite and carbonatite are also seen. The nepheline syenites are well developed at the borders and shows mesoscopic folds. The *Kunduluru* nepheline syenite is a smaller body occurring in the north and is seen as two parallel bands but having the same petrology as the Kunavaram nepheline syenite. The nepheline syenite pluton of *Khariar* intrusion (Fig.4E-9a) is a 30 m long concordant body, which consists of syenite and nepheline syenite, besides alkali granite, gabbro, essexite, malignite, shonkinite and lamprophyre. Amphibole, pyroxene and biotite are the main constituents, besides nepheline and alkali felspar. The pluton has well developed magmatic fabric (Fig.4E-9b) that is concordant with solid-state strain fabric of the associated mylonites, and suggests synkinematic emplacement during thrusting along the mobile belt boundary. The *Bhela-Rajna* alkaline rocks occur to the north and west of Khariar intrusion. These rocks are essentially comendites and riebeckite-, aegirine-, and alkali felspar granite, together with dykes of pyroxenite, syenite and felsic porphyry. Minor occurrences of analcime syenite, quartz syenite, monzonite, granophyre and microgranite are noticed in the contact zone to the north of *Paikmal.* Smaller ultramafic bodies like harzburgite, lherzolite and pyroxenite are also seen nearby. *Koraput* nepheline syenite is a lozenge-shaped small, pretectonic, deformed

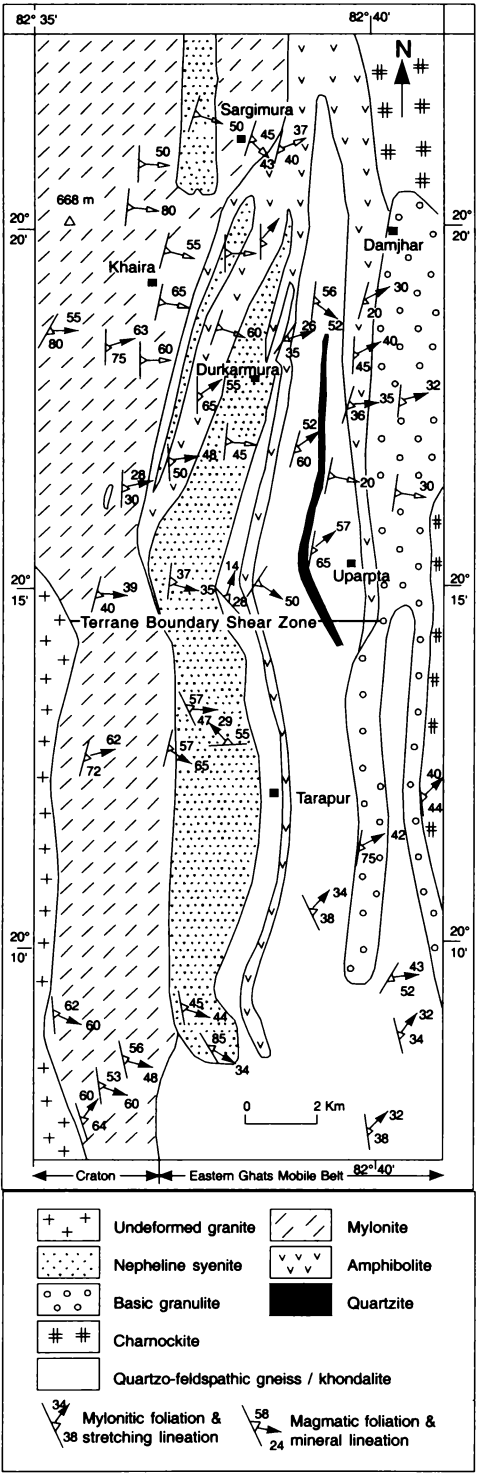

82° 35'
82° 40'
N
Sargimura
668 m
Khaira
Durkamura
Damjhar
Uparpta
Terrane Boundary Shear Zone
Tarapur
20° 20'
20° 15'
20° 10'
0 2 Km
Craton
Eastern Ghats Mobile Belt
82° 40'
Undeformed granite
Nepheline syenite
Basic granulite
Charnockite
Quartzo-feldspathic gneiss / khondalite
Mylonite
Amphibolite
Quartzite
Mylonitic foliation & stretching lineation
Magmatic foliation & mineral lineation

**Fig.4E-9a.** Khariar alkaline pluton and the terrane boundary shear zone of EGMB (modified from Biswal et al. 2004, p.786).

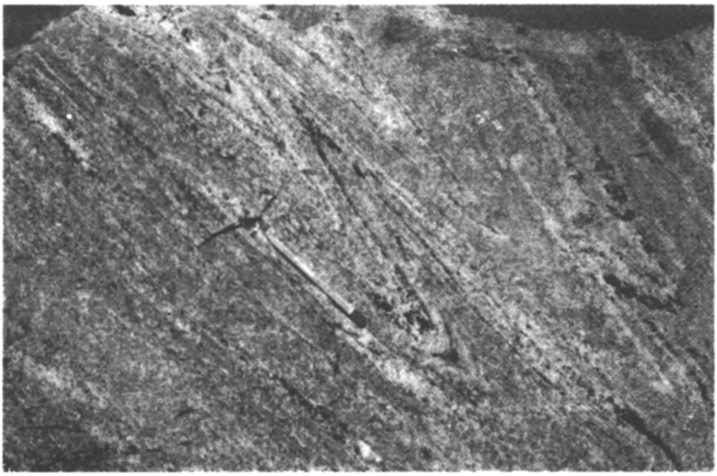


**Fig.4E-9b.** Magmatic folds of layers in Khariar nepheline syenite (Courtesy: T.K. Biswal).

intrusion that occurs within the marginal zone close to the western contact of WKZ. The alkaline intrusion consists of syenite, nepheline syenite and gabbro-norite. The nepheline syenite give an Rb-Sr age of ~850 Ma that may mark a younger event or overprint in the mobile belt.

A series of alkaline rocks occurs in two WNW-ESE trending parallel lineaments in the northern part of EGMB near Redakhol and Kankrakhol (Mazumder et al. 2000). *Redakhol* (*Rairakhol*) nepheline syenite is mafic poor and is associated with syenite, quartz syenite and pegmatite. It shows compositional flow banding that is accentuated by deformation. *Kankrakhol* nepheline syenite occurs as a series of small lensoid bodies of similar composition. The *Baradangua* nepheline syenite occurring farther east in the same alignment may belong to the same group.

Khariar nepheline syenite yields U-Pb age of 1500±4 Ma and Rb-Sr date of 1436±58 Ma, whereas the Redhakhol body has Rb-Sr age of 1413±23 Ma.

## WESTERN CHARNOCKITE ZONE

The WCZ that forms part of the marginal zone of EGMB is subdivided for purpose of description into three sectors, namely, (i) Ongole sector in contact with Dharwar craton, (ii) Jeypur (Jeypore) sector in contact with Bastar craton and (iii) Riamal (Rengali) sector in contact with Singhbhum craton.

*Ongole Sector:* WCZ consists essentially of enderbites with layers and lenses of basic granulites (garnet-pyroxene granulites). BIF bands are associated with enderbites near Ongole. Porphyritic leptynites, described in earlier literature as Bezwada (old name for Vijayawada) gneiss, are associated with enderbites. The rocks of Khondalite Group in this area are typical khondalites, quartzites and calc-silicate rocks. Dehydration melting of biotite has produced garnet-sillimanite and garnet-corundum assemblages in the pelitic gneisses.

The deformation history of this area is not well constrained, but the general pattern is of multiple isoclinal folding with axial planes defined by compositional layering and foliation parallel to the margins of the mobile belt. NW plunging down dip lineation is fairly common. Later folds have axes plunging NE. Shear sense indicates transport of the hanging wall to the NW.

The enderbites yield U-Pb zircon ages of 1700-1720 Ma with $TD_M$ Nd model ages of 2300-2500 Ma suggesting Archaean age of the protoliths. Nd model ages of pelitic gneisses also indicate a provenance age of 2.6–2.8 Ga which correspond to the ages of granitoids of Eastern Dharwar craton. Polyphase metamorphism is indicated by 1.5–1.6 Ga dates by U-Pb and EPMA ages of monazite, and Pb-Pb allanite/felspar ages, which are in accord with 1.5 Ga Rb-Sr isochron for a mangerite.

Layered gabbro-anorthosite complexes of Kondapalli, Chimakurti, Pasupugallu and Ravipadu intrude the charnockites and gneisses of the Ongole sector. The *Kondapalli* intrusion or KLC (Fig.4E-10a) is a discontinuous body consisting of bands of lenses of gabbronorite grading into leucogabbro and anorthosite (Nanda and Natarajan, 1980; Leelanandam, 1997). Layering is well defined by alternating pyroxene and plagioclase layers (Fig.4E-10b). Ultramafic rocks are subordinate and consist of clinopyroxenite and chromite-layered enstatitites. Clinopyroxenite occurs as pods and lenses of varying dimensions with mafic members, whereas enstatitite is confined to anorthosite and leucogabbronorite. Enderbite and charno-enderbite intrude the complex as lit-par-lit injections. Minor intrusions of quartz syenite and alkali granite are seen in the northwestern part of the complex. Quartz bearing rocks at the borders of the complex are probably produced by contamination with host charnockites. Two parental magmas, a magnesian liquid and an Al-rich tholeiite, are proposed for the complex (Leelanandam and Vijaya Kumar, 2004). Low-dipping recumbent folds that are modified by multiple folds of later phases cause complex interference patterns. Allanite and monazite bearing pegmatites intruding the complex are dated at ~1600 Ma. P-T determinations suggest emplacement and fractionation at 1100°C / 8 kbar, followed by near isobaric cooling, along an anticlockwise path at 700°C / 6-7 kbar. UHT metamorphism and crustal anatexis are caused by the thermal effect of the layered intrusion. The *Chimakurti* gabbro-anorthosite complex comprising olivine clinopyroxenite, leucogabbronorite and gabbronorite intrudes khondalites and Mg-Al paragneisses. Similar UHT metamorphic history as in Kondapalli is known for the Chimakurti pluton from studies of Mg-Al pelites. *Pasupugallu*

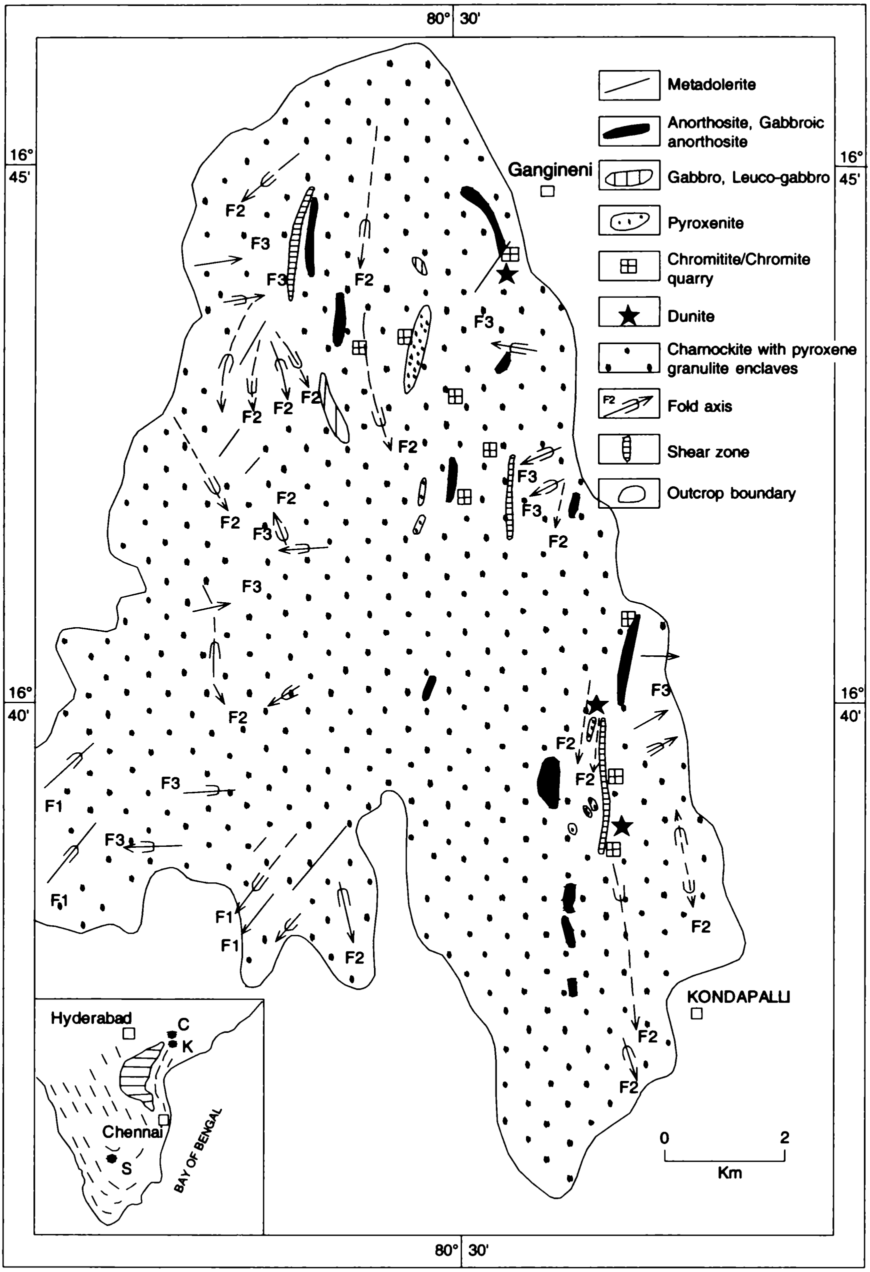

80° 30'
16° 45'
16° 40'
Gangineni
KONDAPALLI
Metadolerite
Anorthosite, Gabbroic anorthosite
Gabbro, Leuco-gabbro
Pyroxenite
Chromitite/Chromite quarry
Dunite
Charnockite with pyroxene granulite enclaves
Fold axis
Shear zone
Outcrop boundary
F1
F2
F3
0 2
Km
Hyderabad
C
K
Chennai
S
BAY OF BENGAL

**Fig.4E-10a.** Geological map of Kondapalli layered complex (after Leelanandam, 1997, with permission from Elsevier). K-Kondapalli, C-Chimalpahad, S-Sittampundi.

syntectonic elliptical pluton consists mainly of gabbro with subordinate gabbroic anorthosite and anorthosite, cut by later alkaline dykes (Nagaraju and Chetty, 2005). The *Ravipadu* pluton consists of gabbro, norite, troctolite and anorthosite (Vijaya Kumar and Ratnakar, 2001)

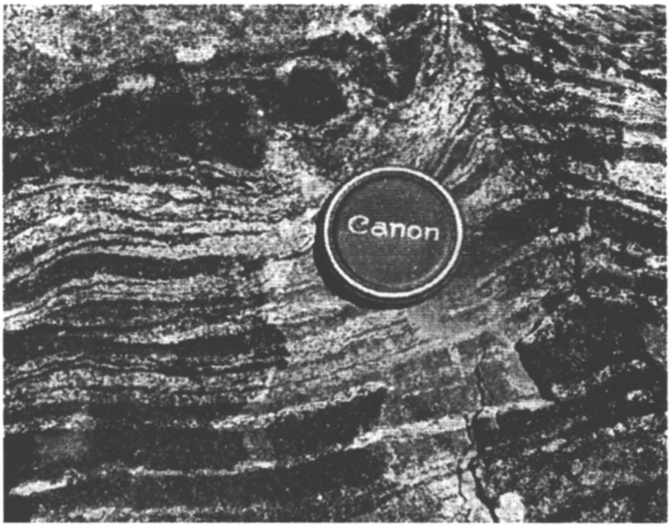


**Fig.4E-10b.** Layered anorthosite of Kondapalli (after Leelanandam, 1997 with permission from Elsevier).

*Jeypur Sector*: The WCZ of Jeypur sector extends along the eastern margin of Bastar craton from Kunavaram to Sambalpur through Jeypur and Junagarh. The prominent Sileru shear zone with top-to-west sense of movement marks the eastern boundary of WCZ. The principal rocks of this sector are enderbites that enclose bands, lenses and xenoliths of basic granulites. Enderbitic rocks are LREE enriched, with negative Eu anomaly that is characteristic of calc-alkaline plutonic rocks seen in Andean margins.

Extensive bodies of basic granulites occur near Machkhund and Balimela. Some basic granulites may be igneous cumulates, whereas others may be metavolcanics, but are indistinguishable in their highly recrystallised, deformed and metamorphosed state. The protoliths of basic granulites may be poorly fractionated tholeiites, strongly depleted in LREE. In the area between Junagarh and Sambalpur, the WCZ is not exposed and the cratonic gneisses and granitoids are in direct juxtaposition with the Central Migmatite Zone of EGMB.

Deformation history in this sector is better known only in the marginal areas. The earliest deformational event is the gneissic banding that is axial planar to a set of rootless isoclinal and reclined folds. The next phase of deformation causes pervasive N-S shear fabric and is related to regional fold closures. The last phase of deformation is less intense and causes warps and broad folds on E-W axes. Thermobarometric studies of calc-silicate rocks and amphibolites near Deobhog indicate 900°C at ~9.5 kbar during peak metamorphism followed by decompression at 750–850°C / 6-7 kbar.

$TD_M$ Nd model ages of 2.9 to 3.9 Ga suggest formation of igneous protoliths before 3 Ga. U-Pb data from zoned zircons points to granulite facies metamorphism at ~2.8 Ga.

*Riamal (Rengali) Sector*: Numerous large E-W trending shear zones, known by various local names, traverse this sector. Charnockites of dioritic to granitic composition form the principal rock types of Riamal-Rengali area. Enderbites and mafic granulites form concordant lenses within charnockites. Some workers assign the charnockites to a separate unit called the Badarama Complex. The associated supracrustal rocks are essentially sillimanite quartzites and pelitic schists that are correlated with Daitari or Bonai Groups of Singhbhum craton. These supracrustal rocks are probably tectonically interleaved with charnockites. Apart from the major ultramafic rocks of Sukinda and Nausahi, minor ultramafic rocks like lherzolite and orthopyroxenite are found at many places, as at Baudh for example. Pronounced WNW-ESE structural trend results from tight to isoclinal folding on E or W plunging fold axes, with the pervasive foliation being axial planar to these folds. Mylonitic foliations with major shear zones indicate NW directed compression.

Amphibolite facies supracrustal rocks of Daitari Group with garnet-staurolite-kyanite assemblage indicate PT conditions of 550-700°C at >5 kbar. Higher peak temperature-pressure conditions are indicated by the presence of garnet-hornblende gneisses, as well as incipient and massive charnockites.

Pb-Pb zircon SHRIMP ages and Pb-Pb zircon ion probe ages of 2800 Ma for hornblende orthogneisses, along with 2750 Ma Rb-Sr WR isochron ages of charnockites in Riamal area indicate a prominent magmatic event at 2.8 Ga. Younger metamorphic ages of 700-800 Ma and Palaeozoic ages of movement along fault zones are reported from this area.

## WESTERN AND EASTERN KHONDALITE ZONES

### Western Khondalite Zone

Khondalites dominate the areas near Koraput and Kalahandi, immediately to the east of the WCZ and the Sileru shear zone. The WKZ extends to the east up to Araku, Rayagada, Bolangir, Rengali and Angul. Besides the main paragneisses, sillimanite-garnet quartzites are well developed locally. Carbonate facies rocks are restricted to the Koraput, Bhavanipatna, Katabhanji, Rayagada and Araku areas. Bedded manganese cherts (now manganiferous quartzites) associated with calc-silicate rocks and pelites are well developed in WKZ (e.g., at Nishikal) in a 150 km long belt. Marbles are, however, rare. Numerous basic-ultrabasic bodies intrude the khondalites between Riamal and Angul.

*Origin:* There were differing views on the origin of khondalites. They are described as palaeosols, felsic volcanics and volcaniclastics, or greywacke-argillite suite. Geochemical studies have confirmed that they are not palaeosols or felsic magmatic products, and are most probably of pelite-greywacke association. The associated leptynites are interpreted either as arkoses or S-type granitoids.

## Eastern Khondalite Zone

This zone is well developed around Visakhapatnam, where the khondalites and associated leptynites were described in earlier literature as *Kailasa gneiss.* The zone continues to the north near Chilka Lake and disappears under Phanerozoic sediments. Calc-silicate rocks, marbles and manganese silicate rocks (earlier mistakenly described as kodurites) that are similar to the queluzites of Brazil, are important units near Garividi and Garbham.

Structural studies in WKZ and EKZ show that the first episode of folding along with its axial planar foliation is contemporaneous with granulite facies metamorphism and conforms to the main Eastern Ghats trend. The second episode of folding produced c-axial tight folds resulting in hook-shaped folds as seen in khondalite. The third episode of folding produced asymmetric folds uniformly plunging NE to NNE. Interesting occurrences of sheath folds are reported in the EKZ from near Visakhapatnam. Structural studies further reveal that ellipsoidal incipient charnockites do not represent remnants of stretched enderbites but are found to have formed *in situ* within leptynite, late in the deformational history. Patchy charnockites have lower Rb/Sr ratios and higher Ba content than the host leptynites. These patches have given Pb-Pb zircon age of ~2700 Ma, that corresponds with the older conventional zircon U-Pb ages of >2600 Ma from khondalites of Puri.

UHT metamorphism (>1000°C, 8-9 kbar) is reported from several areas of EGMB based on studies of sapphirine and spinel bearing Mg-Al granulites and calc-silicate granulites. This high-grade metamorphism is accompanied by high-density $CO_2$ fluid inclusions. These studies show that EGMB granulites are polymetamorphic, showing the impress of two high-grade events. The $M_1$ metamorphism is regarded as having peaked either at 1400 or 1100 Ma ($M_1$). These IBC granulites were affected by $M_2$ metamorphism at 850°C and 8-8.5 kbar. A later event of weak metamorphism associated with hydration was also suggested. In view of the polymetamorphism, P-T-t path as applicable to the whole of EGMB could not be worked out with confidence.

Sm-Nd WR isochron ages of orthogneisses from Rayagada indicate an age of 1.45 Ga, which corresponds to the age of Khariar alkaline complex at 1.45-1.50 Ga. Kommalapadu charnockite also gives Rb-Sr WR age of

~1500 Ma. U-Pb detrital zircon ages suggest depositional ages of khondalite at 1.35 Ga. U-Pb zircon and Pb-Pb isochron age of orthogneisses from Angul area show an age range of 1.12 to 1.15 Ga. Calc-silicate rocks indicate U-Pb titanite cooling ages of 530-570 Ma.

### *Anorthosite Plutons*

Massive anorthosites are emplaced in WKZ and EKZ, the largest of which is the *Bolangir* (*Balangir*) massif (450 km$^2$), followed by that of Chilka Lake, Turkel and Jugsaipatna. Bolangir massif (Fig.4E-11) appears to be a phacolithic dome with a fine-grained melanocratic ferrodiorite border facies. The massif is separated from the host gneisses by garnetiferous leucogranite that is interpreted as derived from a coeval, crustally derived melt. The anorthosite is probably emplaced after the early isoclinal folding and is syntectonic with the later reclined folds. The massif consists essentially of

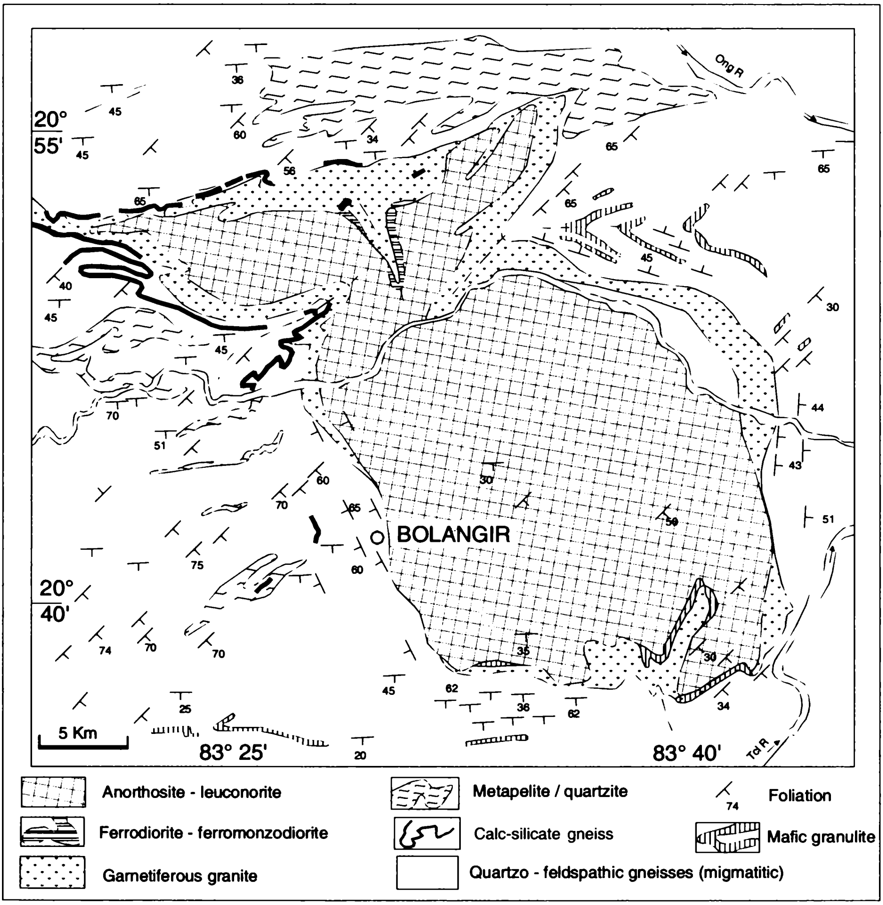

20° 55'
20° 40'
83° 25'
83° 40'
BOLANGIR
5 Km
Ong R
Tel R
Anorthosite - leuconorite
Ferrodiorite - ferromonzodiorite
Garnetiferous granite
Metapelite / quartzite
Calc-silicate gneiss
Quartzo - feldspathic gneisses (migmatitic)
Foliation
74
Mafic granulite

**Fig.4E-11.** Bolangir massif anorthosite (modified from Raith et al. 1997).

anorthosite, anorthositic norite and noritic anorthosite with plagioclase having average composition of ~ $An_{65}$. Orthopyroxene dominates over clinopyroxene and hornblende is nearly absent. Biotite, garnet and quartz are in minor amounts. The masssif contains xenoliths of garnet-pyroxene granulite. The anorthosite is associated with fayalite bearing charnockite. Geochemical studies reflect progressive plagioclase accumulation towards the felsic members of the suite. The ferrodiorites have exceptionally high concentrations of HFSE and REE that probably suggest residual liquids enriched in zircon, monazite, apatite etc. Ferromonzonite is a hybrid between ferrodiorite and the crustal felsic melts. A single episode of protracted intrusion at a depth of 15-25 km corresponding to 675°C at 6 kbar is estimated for Bolangir anorthosite. U-Pb zircon data provide an upper intercept age of 933±82 Ma for ferrodiorite and a concordant Pb-Pb SHRIMP age of 918±20 Ma for garnetiferous leucogranite that borders the pluton. *Chilka Lake* anorthosite (250 sq.km) consists of isolated, but closely spaced plutons of Balugaon and Rambha leuconorite and Khalikot quartz mangerite. The anorthosite is closely associated with rapakavi granite, monzodiorite and Fe-rich diorite. Apart from plagioclase, orthopyroxene is the dominant mineral, followed by clinopyroxene, and amphibole is nearly absent. Ilmenite, magnetite and zircon are common accessories. The complex shows inch scale layering of compositional, gravity or flow type and therefore is transitional between massif and layered anorthosite. Chilka Lake anorthosite is regarded as forceful domical intrusion emplaced at 600-670°C / 5-6 kbar. U-Pb zircon age of the anorthosite is 792±2 Ma. The plutons consist of two suites, namely, (i) a consanguineous anorthosite-leuconorite-norite-jotunite association, and (ii) a cogenetic quartz mangerite-granite association. The anorthosite is intruded by gabbro. Xenoliths of basic granulites and orthogneisses are seen in Balugaon dome. Wollastonite skarn has developed in calc-silicates at the contact of the Rambha intrusion. Anorthosite autoliths are also found within norite. *Turkel* anorthosite (7 sq. km) having plagioclase ($An_{55}$), orthopyroxene and clinopyroxene intrudes khondalites and granite gneisses. *Jugsaipatna* anorthosite near Bhawanipatna is another small body containing olivine norite and troctolite, besides anorthosite. Green spinel occurs as clots in anorthosite. Turkel and Jugsaipatna anorthosites may be satellite bodies of Bolangir anorthosite. Smaller anorthosite bodies are also seen at *Angul.*

## CENTRAL MIGMATITE ZONE

This zone occurs in the middle of EGMB sandwiched between the two khondalite zones WKZ and EKZ. It is well developed to the west of Brahmapur (Berhampur) up to Vamsadhara lineament, in Phulbani area up to the Mahanadi graben as well as in the Srikakulam, Vijayanagaram (Vizianagaram) and Araku valley areas of Andhra Pradesh. The characteristic feature of this zone is the extensive anatexis and migmatisation of all rock types, and prominent development of structural domes and basins. Migmatitic hornblende orthogneisses and leptynites are closely associated with charnockites and show typical examples of incipient or arrested charnockite development. Porphyritic charnockites with megacrysts of perthite are common in shear zones, and as separate intrusive bodies. Garnetiferous granite domes, closely similar in many respects to leptynites are fairly common. Charnockites and khondalites enclose lenses and bands pyroxene granulite, which may be basic sills or flows. Khondalites occur as enclaves in granitic rocks. Marbles and calc-silicate rocks show flowage features resulting in emplacement as veins that are often mistaken for atypical carbonatites without fenitic borders as seen at Borra, Bhowanipatna and other places. Structural studies in this complex zone are too meagre to make any generalization.

Mg-Al granulites are dated by common lead method at 1099±56 Ma, which corresponds to Pb-Pb SHRIMP ages of 1105±56 Ma for zircons from leptynite in Phulbani area. U-Pb and Pb-Pb SHRIMP ages of numerous porphyritic granitoids range between 955 and 985 Ma. U-Pb monazite ages of meta-sedimentary and meta-igneous rocks have a span of 954-973 Ma. Pb-Pb single zircon evaporation ages of Mg-Al granulites are 946-952 Ma. EPMA monazite dates clustering around 950 and 1050 Ma indicate regional deformation accompanied by pervasive metamorphism of about 950-1100 Ma, which marks the peak of Eastern Ghats orogeny. Emplacement ages of some anorthosites, younger granites, rare alkaline rocks and regional thermal events defined by multiple mineral ages suggest post-peak metamorphic cooling between 800 and 850 Ma. Younger event at 500 Ma defined by a host of mineral ages may mark a major thermal episode in the mobile belt.

## TECTONIC EVOLUTION

The various stages of evolution of Eastern Ghats mobile belt from a synthesis of foregoing data and interpretation are summarized and presented in Table 4E-2.

1. The western margin of EGMB is situated at the eastern margin of the Dharwar and Bastar cratons, and the northern margin is placed at the southern boundary of the Singhbhum craton. The contact is marked by a marginal zone extending from the eastern faulted contact of the Proterozoic platform basins ('Purana' basins) of Cuddapah, Chhattisgarh, Indravati etc. Elsewhere, the contact is a sharp thrust zone as in the Khariar area, or marked by a series of parallel shear zones south of the Singhbhum craton as at Riamal and Rengali. The craton-mobile belt contact is marked by a

**Table 4E-2.** Event Stratigrpahy of EGMB

| Age (Ma) | Event | |
|---|---|---|
| 550-650 | Exhumation and stabilisation (=Pan-African) | |
| 800-850 | Emplacement of anorthosite massifs, some alkaline rocks (?), younger granitoids and charnockites | |
| 950-1100 | Main Eastern Ghats orogeny (=Grenville) | |
| | Khondalite Group | Garnet-sillimanite-graphite gneiss (khondalite) with minor cordierite-sapphirine-spinel gneiss (Mg-Al gneiss)<br>Calc-silicate rocks and rare marbles<br>Quartzites (garnet±sillimanite) |
| ~1500 | Emplacement of alkaline rocks along the rift margins | |
| 1800-1600 | Evolution of platform ('Purana') basins like Cuddapah, Chhattisgarh, Indravati etc.<br>Evolution of Nellore-Khammam schist belt in Dharwar craton | |
| 2600-2800 | Charnockites and gneisses of the basement (WCZ) | |

gradual metamorphic transition like in any oblique cross section, but the passage is speeded up along the boundary fault on the cratonic side of the transition zone. Charnockites of WCZ form part of the marginal zone. Beyond the transition zone, the mobile belt emerges abruptly across a ductile shear zone (e.g. Sileru shear zone in EGMB). The NW-SE trending Bhopalpatnam and Karimnagar granulite belts, together with their concordant high-grade Sukma and Warangal enclaves, are juxtaposed against the NNE-trending EGMB at Konta and Khammam respectively. Similarly the WNW-ESE trending Bengpal belt of Bastar craton is truncated at the transition zone near Jeypur. Further north of Bengpal belt, the cratonic trend lines are nearly sub-parallel with EGMB trend with the result no abrupt juxtaposition is found. In the south of Godavari valley, the prominent Nellore-Khammam schist belt has parallelism of tectonic trends with EGMB, but its restricted development within Dharwar craton shows that it may be older (>1800 Ma) than the evoluton of EGMB.

2. The mobile belt is longitudinally divided into four lithological zones from west to east, namely, the Western Charnockite Zone (WCZ), Western Khondalite Zone (WKZ), Central Migmatite Zone (CMZ) and the Eastern Khondalite Zone (EKZ). There have been other attempts to divide the mobile belt into terranes, provinces and/or domains, on the basis of isotope mapping and delineation of boundary faults or shear zones from satellite imagery (Chetty, 2001; Rickers et al. 2001; Dobmeier and Raith, 2003). There are also suggestions that the EGMB to the south of Godavari graben

is different in evolution from the belt to the north of the graben, but the lithotectonic continuity does not confirm this belief.

3. The WCZ is seen all along the margins of EGMB, except between Junagarh and Sambalpur, where WKZ and CMZ tectonically overlie the cratonic gneisses. WCZ consists essentially of enderbites with bands and enclaves of mafic granulites, which give protolith ages of 2600-2800 Ma that corresponds to the major orogenic culmination in the cratons. The WCZ exposes the mid- to lower crustal level of the craton that is now involved in the Eastern Ghats orogeny.
4. The sedimentation of EGMB commenced with rifting at the passive margin of the Deccan protocontinent, which consists of the amalgamated cratons of Dharwar, Bastar and Singhbhum. Penecontemporaneously, the platform basins (Cuddapah, Chhattisgarh etc.) evolved as epi-cratonic basins. A major rifting event marking the beginning of EGMB is evidenced by penecontemporaneous alkali magmatism at the shoulders of the rift during ~1500 Ma (Kunavaram, Khariar, Redakhol and Prakasam alkali province). These alkaline bodies are sited at the edge of EGMB close to the boundary shear zone (Sileru shear zone) and have become nepheline gneisses during orogenic progression. This alkali magmatism initiating the rift is followed by continental margin sedimentation of Khondalite Group consisting of quartzites, pelites (khondalites), minor carbonates, marls and manganiferous sediments. Mg-Al sediments that are subordinate, have been produced by denudation of mafic rocks. They are affected by UHT metamorphism in the contact aureoles of basic intrusions. Minor basic sills and probably flows were intercalated with the sedimentary pile. Felsic volcanics and volcaniclastics may also have been present, but are not identifiable in their present metamorphic and deformed state.
5. The most striking structural feature of the EGMB is the gross parallelism of compositional layering and lithological contacts with the general trend of the belt. The trend is a result of successive early coaxial isoclinal folding. The second major event is the development of reclined folds with steep east-dipping axial planes having down dip lineation. Shearing is widespread during this event with the shear sense indicators showing top-to-west sense of movement. Two events of upright folding that interfere to produce dome and basin structures are evident. Extensive anatexis and migmatisation, particularly in CMZ, are probably synchronous with early folding and shearing. This deformational history is applicable to the whole of EGMB.
6. Ultrahigh temperature (UHT) metamorphism of ~1000°C / 8-10 kbar representing lower crustal depths (30-35 km) was recorded at several places in EGMB along an anticlockwise trajectory and this may mark

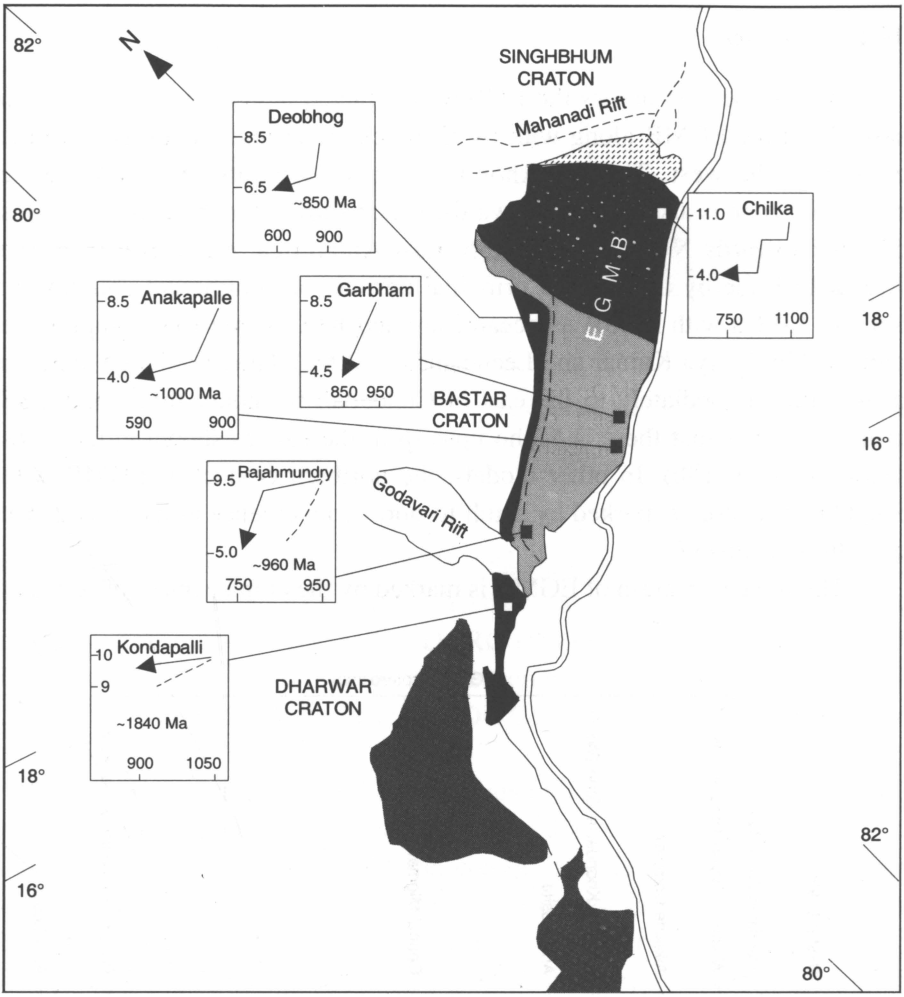

82°
N
SINGHBHUM
CRATON
Mahanadi Rift
Deobhog
8.5
6.5
~850 Ma
600 900
80°
11.0 Chilka
4.0
750 1100
18°
8.5 Anakapalle
4.0
~1000 Ma
590 900
8.5 Garbham
4.5
850 950
E G M B
BASTAR
CRATON
16°
9.5 Rajahmundry
5.0
~960 Ma
750 950
Godavari Rift
10 Kondapalli
9
~1840 Ma
900 1050
DHARWAR
CRATON
18°
82°
16°
80°

**Fig.4E-12.** P-T paths of metamorphism from some sectors of EGMB (after Dasgupta and Sengupta, 2003, with permission from Geol. Soc. London).

a major thermal event. The rocks were invariably cooled at 750 to 800°C. The second major metamorphic event occurred at the peak conditions of 850°C at 8-8.5 kbar followed by a near isothermal decompression to 5 kbar. Although the time of metamorphism could not be well constrained, it appears that the metamorphic events would have occurred between 950 and 1100 Ma.

7. The mobile belt witnessed the intrusion of massif anorthosites, some alkaline rocks (?), late tectonic granitoids and charnockites by about 800-850 Ma, during the waning phase of orogeny. Younger anorogenic events followed during the Pan-African and later periods after crustal stabilisation of EGMB.

## Tectonic Models

A cross section across the EGMB is depicted here (Fig.4E.13a), which shows that the EGMB along with its charnockite basement is thrust onto the cratons in the west. The two khondalite zones separated by an anatectic migmatite zone is also thrust westwards, which shows that the compression is directed towards NW probably from East Antarctica, especially from the Archaean Enderby Land. Two principal periods of continental collision at 1.6 and 1.0 Ga with NKSB as oceanic arc and KLC as arc-root complex are proposed by Vijaya Kumar and Leelanandam (2008). Gravity picture shows a dense crust immediately to the east of Cuddapah boundary thrust and DSS profile suggests that there is Moho upwarp in the east as shown in the cross section (Fig.4E-13b). In other models, the northern contact of EGMB with Singhbhum craton is marked by south-to-north convergence as a consequence of oblique collision.

The western margin of EGMB is marked by the emplacement of series of

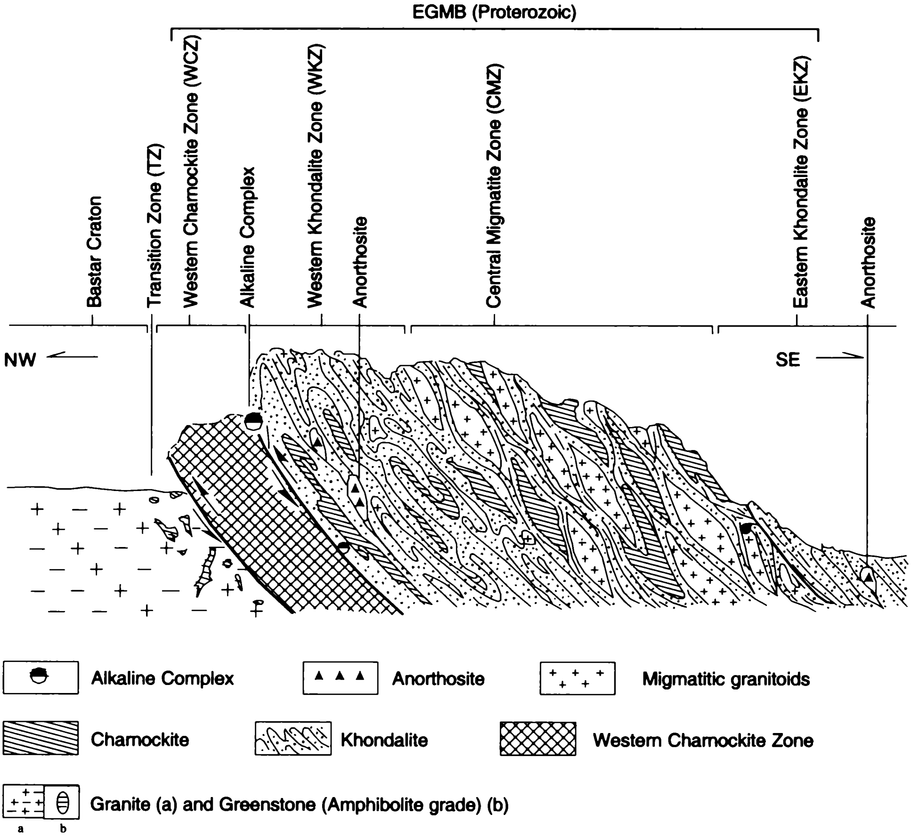

EGMB (Proterozoic)
Bastar Craton
Transition Zone (TZ)
Western Charnockite Zone (WCZ)
Alkaline Complex
Western Khondalite Zone (WKZ)
Anorthosite
Central Migmatite Zone (CMZ)
Eastern Khondalite Zone (EKZ)
Anorthosite
NW
SE
Alkaline Complex
Anorthosite
Migmatitic granitoids
Charnockite
Khondalite
Western Charnockite Zone
Granite (a) and Greenstone (Amphibolite grade) (b)
a
b

**Fig.4E-13a.** Diagrammatic cross section of EGMB (after Ramakrishnan et al. 1998).

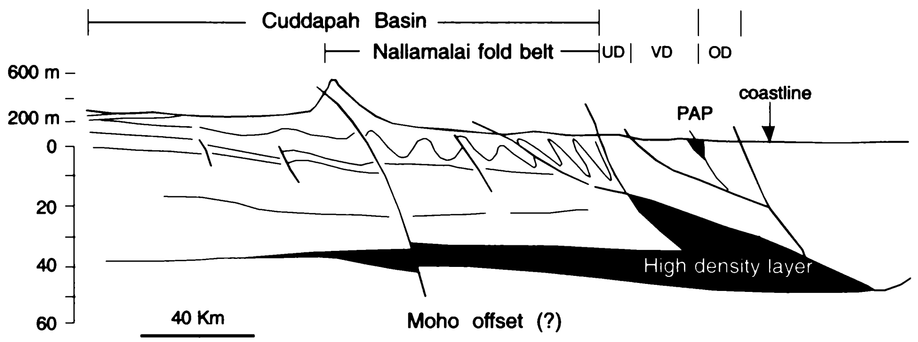


**Fig.4E-13b.** Schematic cross section of the Ongole sector of EGMB (after Dobmeier and Raith, 2003, with permission from Geol. Soc. London). UD - Udayagiri domain, VD - Vinjamuru domain, OD - Ongole domain, PAP - Prakasam Alakaline Province.

alkali rocks and carbonatites that marked the initiation of the belt along a rift. The alkaline rocks and carbonatites are deformed during the Eastern Ghats orogeny. These bodies are called DARC (Deformed Alkaline Rocks and Carbonatites) that mark ancient suture zones during continent-continent collision (Windley, 1993; Burke et al. 2004; Gupta et al. 2005; Leelanandam et al. 2006).

The western margin of WCZ disappears into Bay of Bengal near Ongole, and the western boundary of the marginal zone does not extend beyond Pulicat Lake in the south. The Fermor Line, coastal boundary faults, Mettur shear zone or even Nallamalai fold belt extension do not link up with EGMB as believed earlier by many workers (*see* Ramakrishnan et al. 1998; Gopalakrishnan, 1998). It is however possible that the southern extension of Cuddapah boundary fault may pass through Kalahasti, Wallajah and Tirukoilur up to MBSZ. This line marks the southern extension of Nallamalai fold belt. The western boundary of the fold belt runs parallel to its eastern boundary and links up with MBASZ near Attur, east of Salem (*see* Fig.3D-1).

The lithotectonic polarity of Pandyan mobile belt does not match with EGMB in any type of reconstructions. Marbles are abundant in Pandyan mobile belt supporting cement factories, whereas they are scarce in EGMB. Manganese formations are scattered throughout the EGMB, whereas they are absent in PMB. Quartzites are subordinate in EGMB, whereas they are more widespread in Pandyan mobile belt. The principal ages of Eastern Ghats orogeny are 1.6 and 1.0 Ga, whereas Pandyan mobile belt has a significant Pan-African (500-650 Ma) impress. They may form intersecting mobile belts in models of reconstruction of Rodinia, which is an interesting exercise for the future.

# PANDYAN MOBILE BELT

## INTRODUCTION

Pandyan mobile belt (PMB) (Fig.4P-1; Fig.3D-2; *see* Mem. Geol. Soc. India No.50, 2003, pp.6-7) is the name given to the southern part of granulite terrain of south India, situated to the south of Palghat-Cauvery shear zone or PCSZ (Ramakrishnan, 1988, 1993; Project VASUNDHARA, 1994). PMB contains limestone deposits that support cement plants, minor graphite deposits, gemstone occurrences, ornamental granite and placer deposits of monazite, ilmenite and other 'heavies'. This mobile belt is becoming widely known as Southern Granulite Terrain (SGT), but such a terminology is anomalous, misleading and semantically incorrect, because the large charnockite massifs of the south Indian granulite terrain like the Nilgiri, Biligirirangan, Chitteri, Kallarayan, Shevaroy, Javadi, Kollimalai, Pachaimalai etc are situated to the *north* of the terrain boundary shear zone (PCSZ). Further, various authors have defined SGT in different ways leading to an ambiguity that comes in the way of clearer understanding of the nature and evolution of the high-grade terrain. Initially, the definition of SGT coincided with the Charnockite Province of Fermor (1936). It denoted the granulite terrain to the south of the orthopyroxene isograd (or Fermor Line) up to the southern tip of India at Kanyakumari. But this definition proved to be inadequate, as it included both the Archaean and Neoproterozoic granulites with their distinctive differences in regional geological setting. Vemban et al. (1977) first pointed out this critical difference, which was later extended to a large canvas of the whole of south India by Drury et al. (1984). This important distinction necessitated the division of the granulite terrain of south India into two different tectonic provinces. Accordingly, Ramakrishnan (1988,1993) defined the granulite terrain occurring to the south of Palghat-Cauvery shear zone (PCSZ) as Pandyan mobile belt, to distinguish it from the granulite terrain of the Dharwar craton situated immediately to the north of PCSZ. Project VASUNDHARA (1994) adopted this definition. There is, however, a recent suggestion on the basis of Sm-Nd isotopic mapping (Bhaskara Rao et al. 2003) and U-Pb dating of zircon and monazite (Ghosh et al. 2004) that the dividing line be placed at the newly identified, V-shaped Karur-Kambam-Painavu-Trichur shear zone (KKPTSZ), instead of the PCSZ. This proposed new division corresponds *partly* with the terrane classification of Gopalakrishnan (2001) for the region to the south of

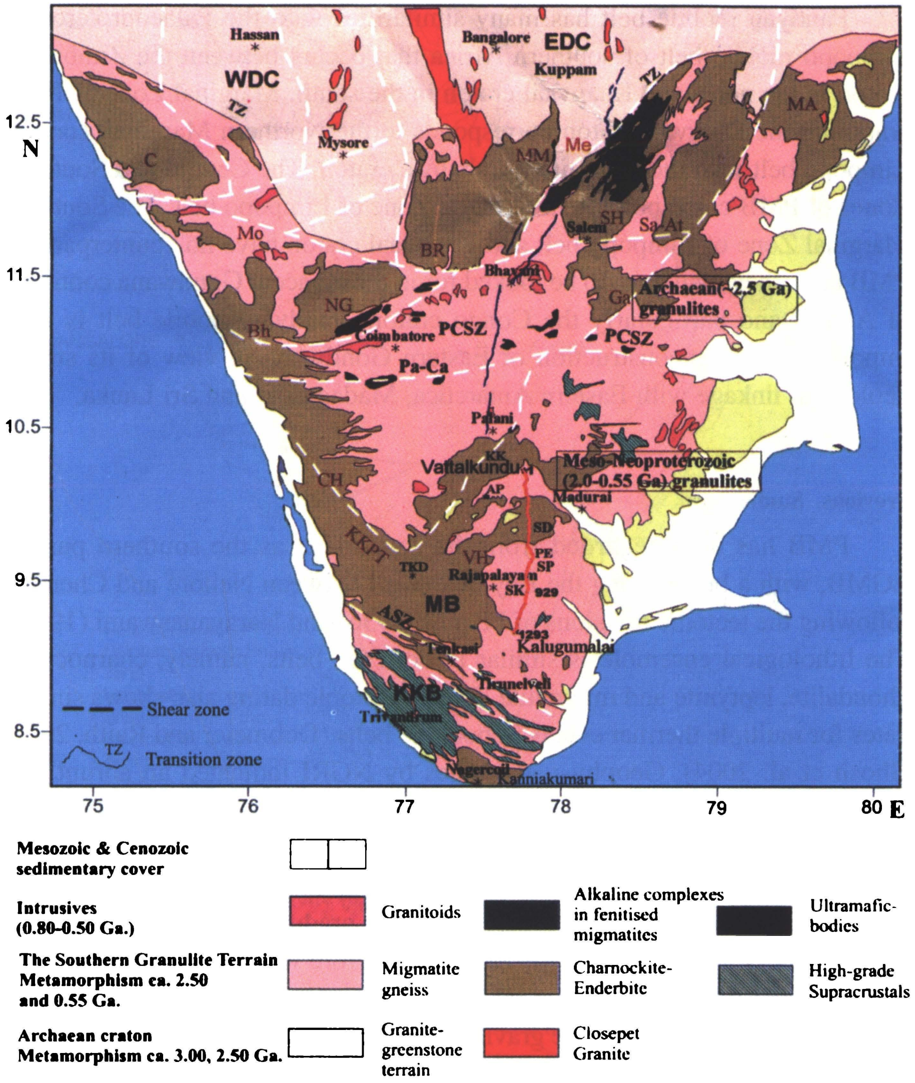

Hassan
WDC
TZ
Mysore
Bangalore
EDC
Kuppam
TZ
MA
C
MM
Me
Mo
SH
Salem
Sa-At
BR
Bhavani
Archaean(~2.5 Ga) granulites
Ga
NG
Coimbatore
PCSZ
PCSZ
Bh
Pa-Ca
Palani
KK
Vattalkundu
Meso-Neoproterozoic (2.0-0.55 Ga) granulites
Madurai
CH
AP
SD
KKPT
VH
PE
SP
TKD
Rajapalayam
SK
929
MB
ASZ
1293
Kalugumalai
Tenkasi
Tirunelveli
KKB
Trivandrum
Nagercoil
Kanniakumari
Shear zone
TZ
Transition zone
12.5
N
11.5
10.5
9.5
8.5
75
76
77
78
79
80 E
Mesozoic & Cenozoic sedimentary cover
Intrusives (0.80-0.50 Ga.)
Granitoids
Alkaline complexes in fenitised migmatites
Ultramafic-bodies
The Southern Granulite Terrain Metamorphism ca. 2.50 and 0.55 Ga.
Migmatite gneiss
Charnockite-Enderbite
High-grade Supracrustals
Archaean craton Metamorphism ca. 3.00, 2.50 Ga.
Granite-greenstone terrain
Closepet Granite

**Fig.4P-1.** Geological map of the South Indian Granulite terrain. Major geological domains: Western and Eastern Dharwar cratons (WDC, EDC); Madurai Block (MB) and Kerala Khondalite Belt (KKB); The highland massifs: Nilgiri (NG); Coorg (C); Biligiri Rangan (BR); Malai Mahadeswara (MM); Shevaroy (SH); Chennai (Madras, MA); Cardamom (CH) and Varshanadu (VH). The prominent shear zones: Moyar (Mo); Bhavani (Bh); Palghat-Cauvery Shear Zone (Pa-Ca); Salem-Attur (Sa-At) and Gangavalli (Ga). The Karur-Kambam-Painavu-Trichur (KKPT) and Achankovil Shear Zone (ASZ), Me - Mettur Fault; Andipatti (AP), Kodaikanal (KK), Periyar (PE), Sarvathapuram (SP), Sedapatti (SD), Sivakasi (SK) and Tekkadi (TKD). Kuppam-Palani (black line)-Kalugumalai-Vathalagundu (red line) Transect (N-S) shown in middle (Rajendra Prasad et al. 2006).

PCSZ, but is inconsistent with the lithological association and regional structure. Detailed geological mapping together with extensive dating may be necessary to verify this proposal for change (*see* Ramakrishnan, 2003).

Pandyan mobile belt has many similarities with the Palaeoproterozoic Limpopo mobile belt of southern Africa that occurs between the Zimbabwe craton in the north and Kaapvaal craton in the south. Marginal Zone of PMB adjoining the Dharwar craton corresponds to the Northern Marginal Zone of Limpopo belt with the adjoining Zimbabwe craton. The Central and Southern Zones of PMB correspond to the Central Zone of Limpopo belt. The Southern Marginal Zone of Limpopo belt and Kaapvaal craton have no counterparts in PMB and they may have to be looked for in the adjacent Gondwana continent of Africa, and particularly the Congo craton. Pandyan mobile belt is very important in the reconstruction of Eastern Gondwana in view of its strong geological linkage with Eastern Antarctica, Madagascar and Sri Lanka.

### Previous Studies

PMB has been regarded from the early days as the southern part of EGMB, with a break along the Bay of Bengal between Nellore and Chennai, following the tectonic divisions of Fermor (1936) and Narayanaswami (1970). The lithological ensemble is similar in both the belts, namely, charnockite, khondalite, leptynite and migmatite. Recent isotopic dating also shows similar dates for multiple thermal events in both the belts (Dobmeier and Raith, 2003; Ghosh et al. 2004). Geophysical studies by NGRI indicated an abrupt and linear gravity high along the East Coast, and this was interpreted to show the southern continuity of EGMB as the Coastal Granulite Terrain (CGT) situated to the east of coastal boundary fault (CBF) in Fig.4P-2a. The granulite terrain to the west of CGT, on the other hand, showed a gradual transition geologically and by gravity anomalies (Fig.4P-2a), and therefore was identified as separate from EGMB. Aeromagnetic surveys, however, indicated clear E-W trends of the basement cutting across the gravity high (Fig.4P-2b), thereby contradicting the gravity interpretation (Reddi et al. 1988). Meanwhile, Palghat-Cauvery shear zone (PCSZ) was identified as a major boundary between disparate crustal blocks (Vemban et al. 1977; Drury et al. 1984). The granulite terrain to the south of PCSZ was therefore called the Southern Granulite Terrain (SGT) to distinguish it from EGMB and the charnockites of Dharwar craton, and this terminology gained wide currency. It was realized that SGT to the south of PCSZ had large volumes of QCP suite, including crystalline limestones supporting cement factories and this denotes a Proterozoic aspect, as against the traditional view of this terrain as Archaean. Rb-Sr isochron of ~550 Ma (Hansen et al. 1985) of gneisses intruding the QCP suite near Madurai showed the strong Neoproterozoic impress on PMB, in stark contrast to the stabilisation of Dharwar craton at ~2500 Ma. A slew of Neoproterozoic ages from various rock types followed (Santosh et al. 2003; Shabeer et al. 2004; Collins et al.

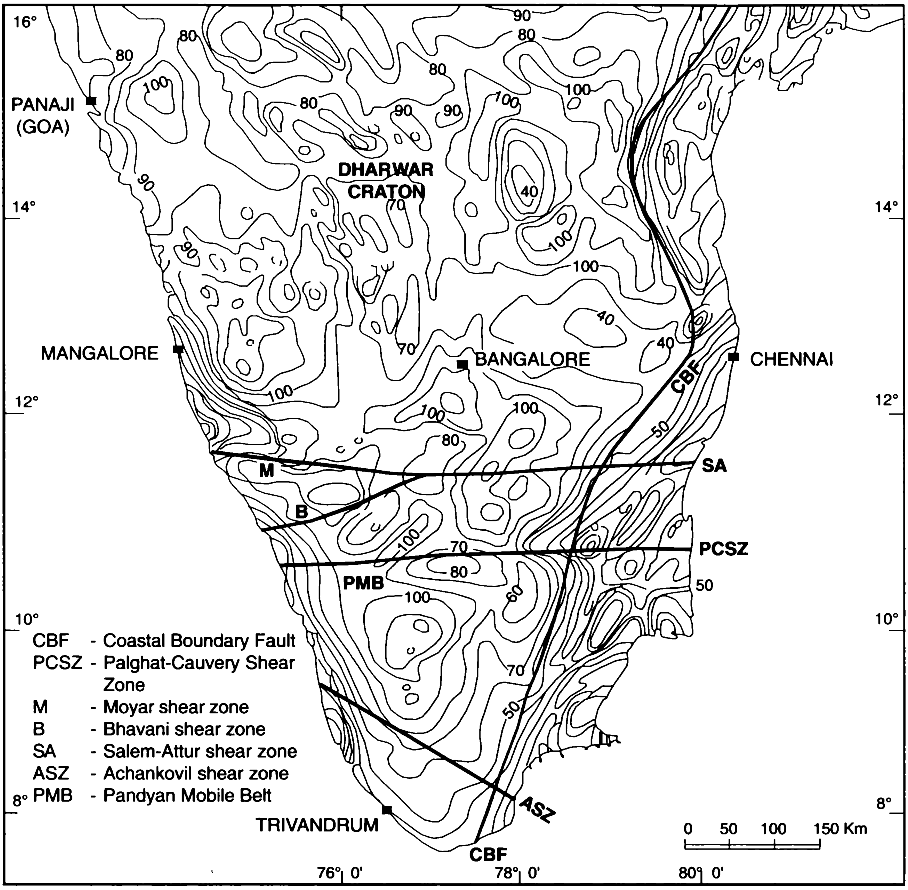

16°
PANAJI (GOA)
14°
MANGALORE
12°
10°
8°
14°
12°
10°
8°
DHARWAR CRATON
BANGALORE
CHENNAI
TRIVANDRUM
CBF
SA
PCSZ
M
B
PMB
ASZ
90
80
100
70
40
60
50
CBF - Coastal Boundary Fault
PCSZ - Palghat-Cauvery Shear Zone
M - Moyar shear zone
B - Bhavani shear zone
SA - Salem-Attur shear zone
ASZ - Achankovil shear zone
PMB - Pandyan Mobile Belt
0 50 100 150 Km
76° 0'
78° 0'
80° 0'

**Fig.4P-2a.** Gravity map of south India with terrain boundaries.

2007). This led to the suggestion that SGT to the south of PCSZ was a Proterozoic mobile belt bounding the Dharwar craton, and was named the Pandyan mobile belt (PMB), after the legendary Pandyan kingdom in the ancient history of south India (Ramakrishnan, 1988, 1993; Project Vasundhara, 1994).

### Relation with EGMB

PMB and EGMB are divided into lithotectonic zones on the lines of zonation described from the Limpopo mobile belt (Ramakrishnan et al. 1998). The divisions are only broadly comparable between PMB and EGMB because of the general lithological similarities, but the mutual geological correlation of lithologies is incompatible, if the zones were to be regarded as once-continuous. For example, the Marginal Zone and WCZ of EGMB may be somewhat similar to the Transition Zone of Dharwar craton and Marginal Zone of PMB, but the fabrics are not conformable, as they are N-S trending instead of E-W, if

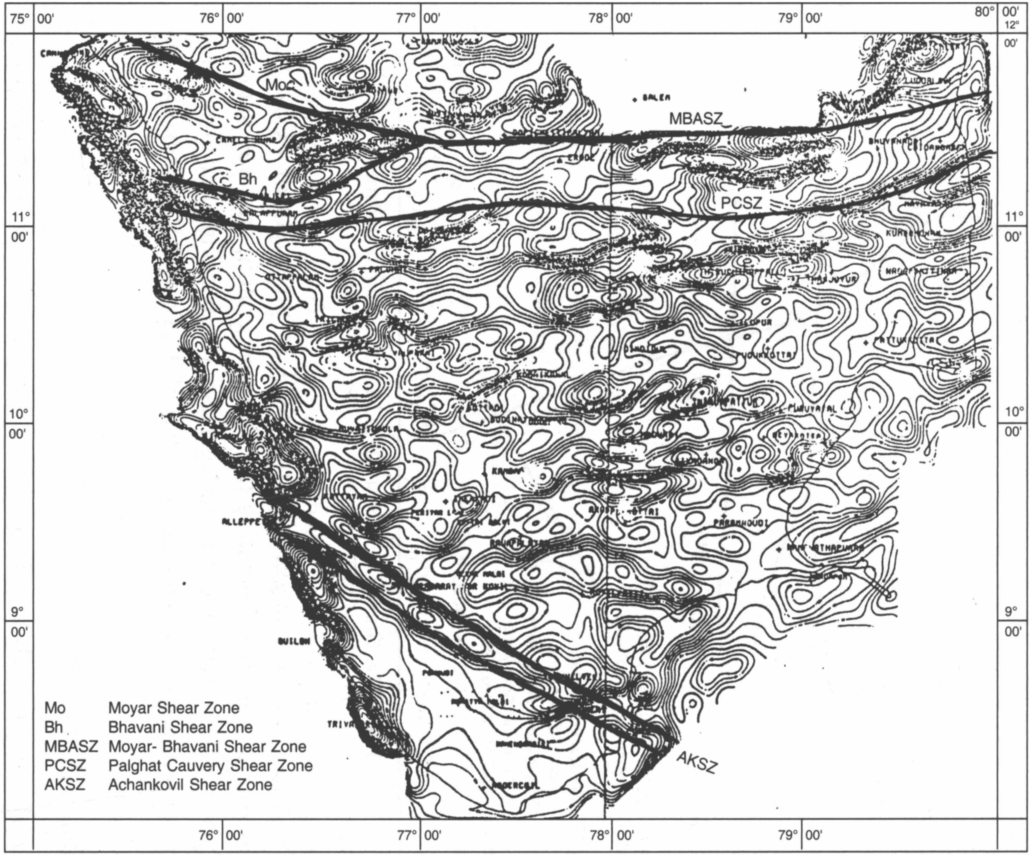

75° 00'
76° 00'
77° 00'
78° 00'
79° 00'
80° 00'
12° 00'
11° 00'
10° 00'
9° 00'
Mo
Bh
MBASZ
PCSZ
AKSZ
SALEM
ALLEPPEY
QUILON
TRIVA
Mo Moyar Shear Zone
Bh Bhavani Shear Zone
MBASZ Moyar- Bhavani Shear Zone
PCSZ Palghat Cauvery Shear Zone
AKSZ Achankovil Shear Zone

**Fig.4P-2b.** Aeromagnetic map of southern India showing crustal scale shear zones marking terrain boundaries (after Reddi et al. 1988). Shear zones as in Fig.4P-2a.

they were to be contiguous. WKZ of EGMB has no counterparts in PMB. CMZ of EGMB is correlatable with Madurai Block of PMB, with similar development of dominant migmatites. EKZ of EGMB is narrow and discontinuous, whereas the prominent straight belt of Trivandrum Block (PMB) to the south of Achankovil Shear Zone has discordant NW-SE trends, and is not comparable. EGMB has a dominant Grenvillian (~1000 Ma) impress in contrast to the widespread Pan-African (550-750 Ma) impress in PMB. Further, mineable manganese horizons found of EGMB have no equivalents in PMB. Similarly, the abundance of quartzites and cement-grade marbles in PMB has no correlatives in EGMB. Both the belts are incompletely preserved, with their dismembered parts to be pieced together from the Gondwanic neighbours. Therefore, until the differences are reconciled by amalgamating the scattered fragments with these mobile belts in East Gondwana, it is better that both the belts are treated independently (*see* Ramakrishnan et al. 1998; Gopalakrishnan, 1998).

### Craton versus Mobile Belt

Important differences between the charnockite terrains of Dharwar craton and Pandyan mobile belt (PMB) (see Ramakrishnan, 2003) are listed below:

(1) The cratonic granulites have dominant N-S structural trends in conformity with those in the rest of the craton, whereas the mobile belt granulites have a conspicuous E-W trend. The cratonic trends swerve into that of the mobile belt along the PCSZ (Fig.4P-3, 4P-4).

(2) The cratonic granulites have attenuated enclaves of greenstone belts and high-grade schists containing a prominent ensemble of mafic-ultramafic rocks in close association with BIF. Quartzite-carbonate-pelite (QCP) suite is subordinate. The mobile belt charnockites, on the other hand, enclose swathes of QCP supracrustals like quartzites, metapelites (garnet-sillimanite-graphite-cordierite-spinel-hypersthene gneisses), calc-silicate rocks and marbles. Mafic-ultramafic rocks are subordinate and BIF is uncommon.

(3) Dharwar craton shows medium-pressure metamorphism (kyanite-sillimanite type) in WDC and low-pressure metamorphism (andalusite-sillimanite type) in EDC, which extend into the cratonic charnockite massifs and terminate at the PCSZ. The mobile belt charnockites, on the other hand, generally show low-pressure metamorphism.

(4) The charnockites of the craton exhibit a dominant thermal event of 2500-2600 Ma related to Dharwar orogeny, with earlier events (3000-3400 Ma) preserved mainly in WDC. The charnockites of Pandyan mobile

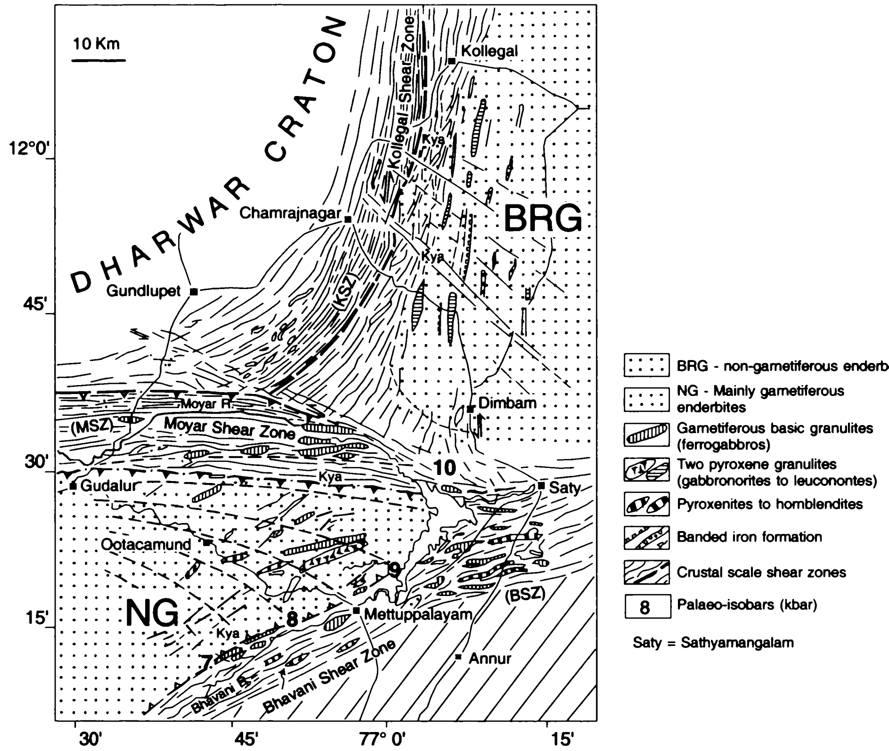

10 Km
DHARWAR CRATON
Kollegal
Kollegal Shear Zone
Kya
Chamrajnagar
BRG
Gundlupet
(KSZ)
Moyar R.
(MSZ)
Moyar Shear Zone
Dimbam
10
Gudalur
Saty
Ootacamund
9
NG
8
Mettuppalayam
(BSZ)
Kya
7
Bhavani R.
Bhavani Shear Zone
Annur
12°0'
45'
30'
15'
30'
45'
77° 0'
15'
BRG - non-garnetiferous enderbites
NG - Mainly garnetiferous enderbites
Garnetiferous basic granulites (ferrogabbros)
Two pyroxene granulites (gabbronorites to leuconontes)
Pyroxenites to hornblendites
Banded iron formation
Crustal scale shear zones
8 Palaeo-isobars (kbar)
Saty = Sathyamangalam

**Fig.4P-3.** Geological map showing the Nilgiri (NG) and Biligiri Rangan (BRG) charnockite massifs at the southern and eastern fringes of the Archaean Dharwar craton. (after Srikantappa 1996, with permission from Elsevier). The charnockite massifs are separated from each other by major crustal-scale shear zones. Kya - Kyanite bearing granulites and quartzites.

belt have a dominant Pan-African impress (550-750 Ma) with vestiges of many earlier events preserved sporadically over wide areas.

(5) There are also significant geochemical changes reported across the PCSZ (Ramachandran and Ramana Rao, 1999; Tomson et al. 2006). Tonalitic and enderbitic gneisses dominate the craton, whereas the mobile belt is enriched in more potassic types. Correspondingly, LILE and LREE are enriched in the mobile belt gneisses.

### Zonation of PMB

Pandyan mobile belt (PMB) is divided into three major tectonic units, namely (1) *Marginal Zone*, (2) Madurai Block or the *Central Zone*, and (3) Trivandrum Block (popularly known as Kerala Khondalite Belt) consisting of Ponmudi Sub-Block and Nagercoil Sub-Block, together constituting the *Southern Zone*. The northern Marginal Zone covers the area between the shear zones MBASZ and PCSZ and consists principally of gneisses, charnockites

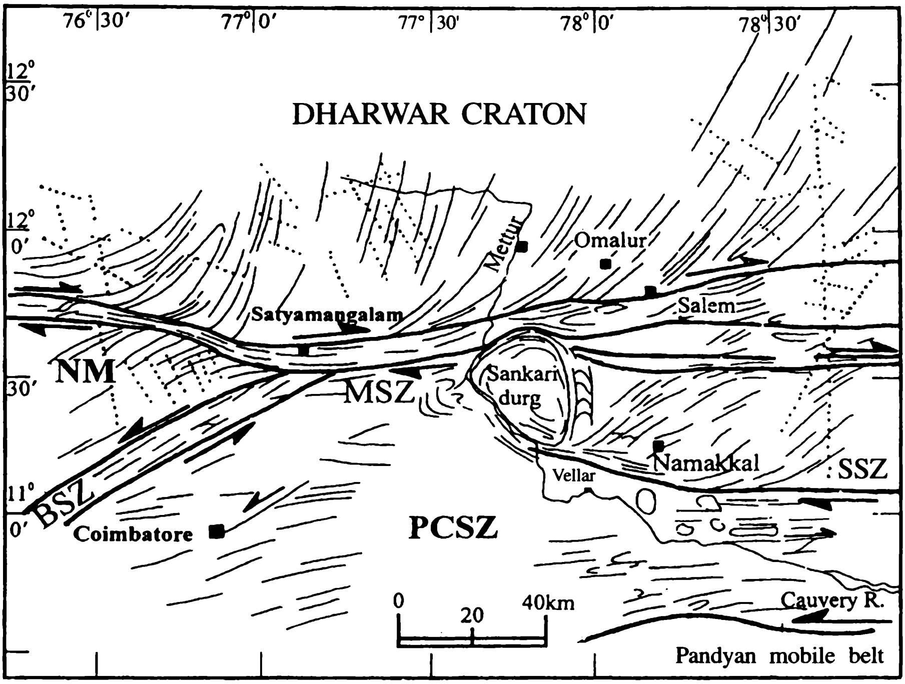


**Fig.4P-4.** Major shear zones between Dharwar craton and Pandyan mobile belt. **NM:** Nilgiri Massif. **MSZ:** Moyar Shear Zone (MSZ) in the Moyar River-Satyamangalam-Salem-Attur area. **BSZ:** Bhavani Shear Zone along Bhavani River. **PCSZ:** Palghat-Cauvery Shear Zone. **SSZ:** Sweta Nadi (Vellar) Shear Zone (after Jain et al. 2003).

and supracrustal enclaves of Dharwar craton, that are tectonically intermingled with supracrustal enclaves (e.g. Madukkarai) and granites (e.g., Sankari) belonging to Pandyan mobile belt. Madurai Block or the Central Zone encompasses the area between the PCSZ and Achankovil shear zone (AKSZ) to the south, and consists essentially of quartzites, Mg-Al pelites, garnet-sillimanite gneisses and calc-silicate rocks (Khondalite Group) occurring as swathes within the hornblende-biotite gneisses, garnet-biotite gneisses and charnockites of the Pandyan mobile belt. This zone is characterised by swirling structural patterns. The Trivandrum Block (Kerala Khondalite belt) or Southern Zone is a prominent straight belt consisting of Ponmudi Sub-Block in the north, and Nagercoil Sub-Block in the south. Kerala Khondalite belt is essentially made of garnet-sillimanite-graphite gneisses, garnet-cordierite gneisses, calc-silicate rocks and marbles, quartzites, pyroxene granulites, garnet-biotite gneisses and garnet bearing quartzofelspathic gneisses, incipient charnockites derived from paragneisses (e.g., Ponmudi), and massive to banded charnockites. Nagercoil Sub-Block consists mainly of massive and banded charnockites, interspersed with enclaves of garnet-cordierite-spinel-sillimanite-hypersthene gneisses, minor calc-silicate rocks and rare quartzites.

## Shear Zones

Several crustal-scale ductile shear zones have been delineated in the contact zone between the Dharwar craton and PMB. *Moyar shear zone* is an ESE trending 200 km long and 10 km wide dextral shear zone that separates he Dharwar craton from the Nilgiri charnockite massif. Originally, a large horizontal displacement along the shear zone was visualized on the assumption that BR Hills and Nilgiri were once aligned together. Although the dextral sense was confirmed by later studies, evidence for large displacement could not be found. Some authors regard this shear zone as an Archaean suture zone on the basis of extensive dates of 2500-2600 Ma determined from a wide variety of rocks in the vicinity. Moyar shear zone extends west into Kerala through Vaithiri and Mattanur to Cannanore (Kannur). Moyar shear zone is apparently truncated by the Bhavani shear zone that extends to the east as *Salem-Attur shear zone*. *Bhavani shear zone*, located to the south of the Nilgiri massif, is usually considered together with Moyar shear zone for tectonic interpretation. Bhavani shear zone extends to the west as Bavali shear zone through Manjeri to Calicut (Kozhikode) in Kerala. Both dextral and sinistral shear sense have been described from this zone. *Mettur shear zone* trending NE links the Dharmapuri-Palar curved fault with the Salem-Attur shear zone. *Palghat-Cauvery (Palakkad-Kaveri) shear zone* is the most important boundary that separates Dharwar craton from PMB. It is a major crustal scale dextral shear zone that has been shown along different alignments in different maps. The shear zone follows roughly the Cauvery (Kaveri) River up to Karur and then follows the course of Noyil (Noyyal) River near Chennimalai up to Coimbatore and therefore known earlier by the more appropriate term of Noyil-Cauvery shear zone instead of the more popular Palghat-Cauvery shear zone. In this region, the shear zone is situated between the last major BIF of Dharwar craton and the first major calc-silicate horizon of PMB. It is traced through the northern margin of Madukkarai-Walayar khondalite-limestone outcrop to the south of BIF bands near Mannarkad and further west via Malappuram to Beypore. In the east and west, the shear zone is lost under younger sedimentary cover. Innumerable bodies of granite, gabbro and gabbroic anorthosite are seen in the vicinity of this large shear zone. Many shear zones parallel to PCSZ are also recorded (Chetty et al. 2003; Jain et al. 2003; Meissner et al. 2002). The newly described *Karur-Kambam-Painavu-Trichur shear zone* (Ghosh et al. 2004) is a curved shear zone and its V-shape is attributed to later refolding. Structural and lithologic discontinuity across the shear zone, as well as 560-570 Ma shearing and magmatism along the shear zone are cited by the authors to show that this shear zone, rather than PCSZ, may mark the boundary between the Archaean Dharwar craton and the Proterozoic terrain of SGT. This needs more detailed studies for confirmation and acceptance (*see* Cenki and Kriegsman, 2005), since the lithological differences and refolding episodes need to be established. *Achankovil shear zone* marking the boundary between the Madurai and Trivandrum Blocks is interpreted either as a sinistral or dextral shear zone (Saks et al. 1997; Guru Rajesh and Chetty, 2006). Some believe that it peters out in Kerala and continues as the parallel Tenmala (Tenmalai) shear zone in Tamil Nadu. It is regarded as not a major terrane boundary (*see* Cenki and Kriegsman, 2005). It has been recently interpreted as the rotated and flattened limb of a regional NW-SE trending fold (Ghosh et al. 2004). Yet another shear zone reported in literature is the sigmoidal *Ganguvalli shear zone* that separates Kollimalai and Pachaimalai granulite massifs. A shear zone off the west coast has been named the West Coast shear zone (Ghosh et al. 2004). Several minor shear zones in the Cauvery shear zone are described by Chetty et al. (2003) and Jain et al. (2003).

## DESCRIPTION OF THE MOBILE BELT

Pandyan mobile belt has a major transitional zone with the Dharwar craton called the Marginal Zone, which is also described by some authors as Cauvery shear zone or Cauvery suture zone.

### Marginal Zone

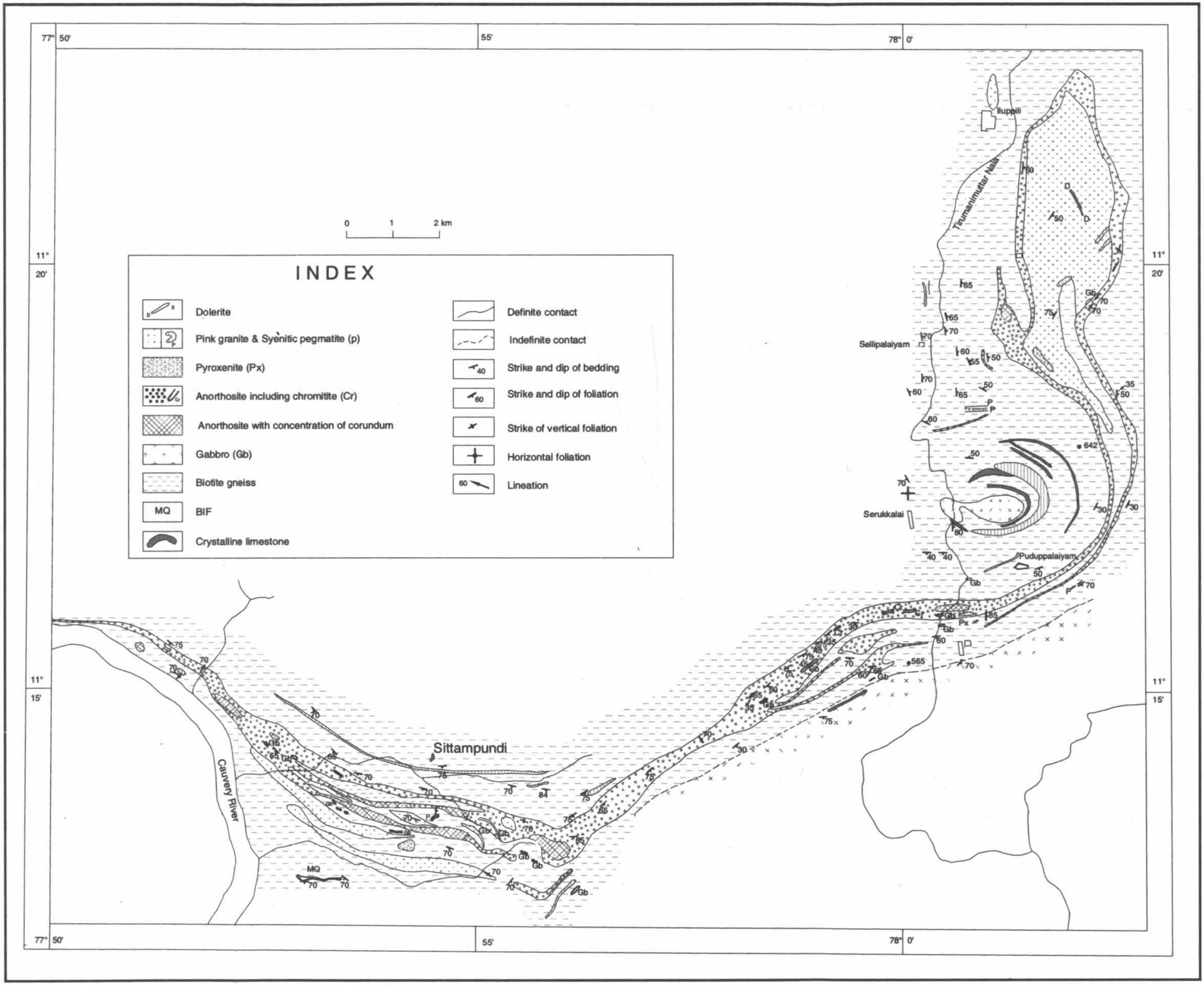
#### Lithological Association

This is a complex zone of interaction between the Dharwar craton and Pandyan mobile belt. The marginal zone is contiguous with the Dharwar craton but for separation by the *Moyar-Bhavani-Attur shear zone* (MBASZ). Cratonic planar and linear structures swing into MBASZ along its length and narrow width (Figs.4P-3, 4P-4) but locally continue uninterruptedly through the MBASZ to the PCSZ.

The marginal zone of PMB is characterised by the presence of a variety of biotite-hornblende gneisses and migmatites called as the Bhavani Gneiss in Tamil Nadu. Some of the gneisses are highly fissile due to intense deformation, but others show augen and banded structures. These gneisses, which continue into this marginal zone from the Dharwar craton, represent the deeper levels of both the Peninsular Gneiss and Dharwar Batholith. Large massifs of charnockite such as the Nilgiri, Kollimalai and Pachaimalai in Tamil Nadu and Wayanad in Kerala occur within the Bhavani Gneiss. Younger granites (Pan-African) like those of Sankari, Karamadai and Punjaipuliyanpatti intrude the Bhavani Gneiss. Incipient charnockite patches are prominent in the Palghat Gap region (Ravindra Kumar and Sukumaran, 2004). The supracrustal rocks that occur as swathes and enclaves in Bhavani Gneiss are Sargur schists to the west of Sathyamangalam. Further west in Kerala, the marginal zone exposes *Vengad Formation* in the isolated Vengad Basin and consists of oligomict conglomerate (locally polymict with granite clasts) near Kuthuparamba, quartz-mica schits with kyanite and cross-bedded quartzite. There are suggestions that this formation may be equivalent of Dharwar sequence, but volcanics are absent here. It is likely to be a pre-Dharwar succession similar to Warangal Group of EDC or a post-Dharwar unit developed locally. To the east of Sathyamangalam, the supracrustals rocks are mainly the BIF-rich Salem (Thiruvannamalai) Group consisting of amphibolites, pyroxene granulites, ultramafic schists, pink granulitic gneisses and BIFs (magnetite quartzite and quartz-magnetite-hypersthene granulite). Another group of rocks consisting of fuchsite-kyanite quartzites, corundum-mica schists, para-amphibolites and calc-silicate rocks are called as Sathyamangalam Group (Gopalakrishnan et al. 1976) as equivalents of Sargur Group. But these may represent enclaves of Eastern greenstone belts, including Sakarsanahalli Formation and equivalents. Some enclaves like those in Sankari granite (marbles, calc-silicate rocks and pelites) may be equivalent of Khondalite Group of PMB that were probably tectonically transported to the Marginal Zone. The marginal zone therefore includes the elements of mainly the Dharwar craton along with subordinate tectonically interleaved elements of PMB.

### Layered Basic Complexes

*Sittampundi Complex:* Another major lithological association of the marginal zone is the Sittampundi and Bhavani (Mettupalayam) layered basic complexes. Sittampundi complex (Subramanian, 1956a; Ramadurai et al. 1975; Janardhan and Leake, 1975) is a dismembered layered basic intrusion within quartzofelspathic gneisses surrounding the Sankari (Sankagiri) dome near Tiruchengode (Fig.4P-5a). The gneisses contain enclaves of amphibolite, marble, calc-silicate rock and BIF. Sittampundi complex is folded in two phases into E-W trending isoclinal antiform followed by a final phase of open folding. Recent structural studies have brought out a major E-W trending fold (Namakkal fold) closing to the west. A syntectonic tonalite emplaced within this fold gives U-Pb zircon age of 2537 Ma. Study of structures to the east of Karur have brought out three E-W trending south-facing thrust sheets stacked on one another separated by zones of mylonite running for tens of kilometres within the marginal zone. Continuation, if any, of these structures to the west of Karur may be useful to understand the structural evolution of the Marginal Zone. The complex consists of layered gabbro and leucogabbro (Fig.4P-5b) with pyroxenite and dunite layers and lenses at the base, followed by chromite-


77° 50'
55'
78° 0'
11° 20'
11° 15'
0 1 2 km
INDEX
Dolerite
Pink granite & Syenitic pegmatite (p)
Pyroxenite (Px)
Anorthosite including chromitite (Cr)
Anorthosite with concentration of corundum
Gabbro (Gb)
Biotite gneiss
MQ
BIF
Crystalline limestone
Definite contact
Indefinite contact
Strike and dip of bedding
Strike and dip of foliation
Strike of vertical foliation
Horizontal foliation
Lineation
Iluppili
Tirumanimuttar Nala
Sellipalaiyam
Serukkalai
Puduppalaiyam
642
565
Sittampundi
Cauvery River
Gb
Cr
Px
P
D

**4P-5a.** Geological map of Sittampundi anorthosite complex, Tamil Nadu.

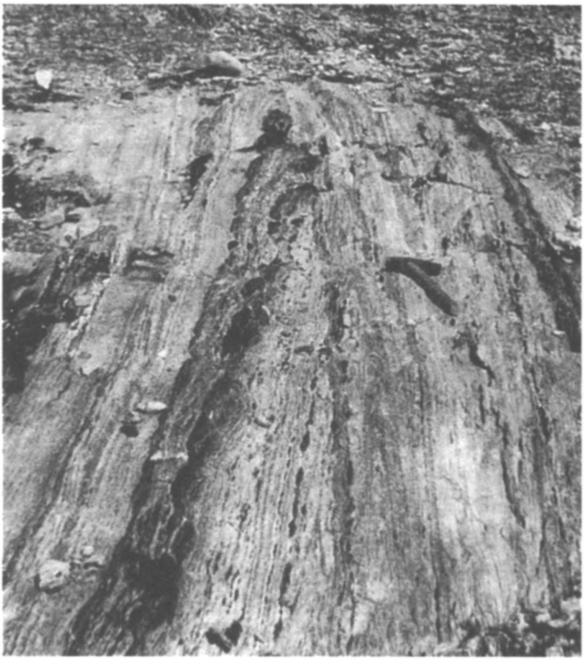


**Fig.4P-5b.** Layered anorthosites, Sittampundi (Subramanian and Selvan, 2001, p.49).

layered hornblende anorthosite and clinozoisite anorthosite at the top. Anorthosite and leucogabbro form the dominant lithology containing less than 10% mafic minerals. The gabbro-anorthosite suite, besides containing the essential minerals of calcic plagioclase, clinopyroxene, hornblende and garnet, consists of olivine, clinozoisite, scapolite, grossularite as well as rare corundum, sillimanite, gedrite and other accessory and opaque minerals. Geochemical studies indicate the derivation of the layered complex by fractional crystallisation from LREE depleted mantle sources. Thermobarometric studies have indicated high pressures of ~12 kb (?) at 750-850° C for the garnet-pyroxene granulite, which was debated and interpreted as eclogite. Isothermal decompression at ~5kb and 600°C followed the metamorphic peak. Sm-Nd whole rock isochron defines the age of the complex at 2935±60 Ma. Still younger ages of ~2000 Ma and 730 Ma recorded in the complex suggest the impress of later events (Bhaskar Rao et al. 1996).

*Bhavani Complex:* This basic complex (also called Mettupalayam complex) occupying the Bhavani shear zone (Fig.4P-6) is essentially an ultramafic-anorthosite suite, which includes dismembered units of dunite, peridotite, pyroxenite (±garnet), garnet gabbro, gabbroic anorthosite, and hornblende anorthosite containing a few impersistent bands of chromite.

Igneous layering and cumulate textures, deformation pattern and geological

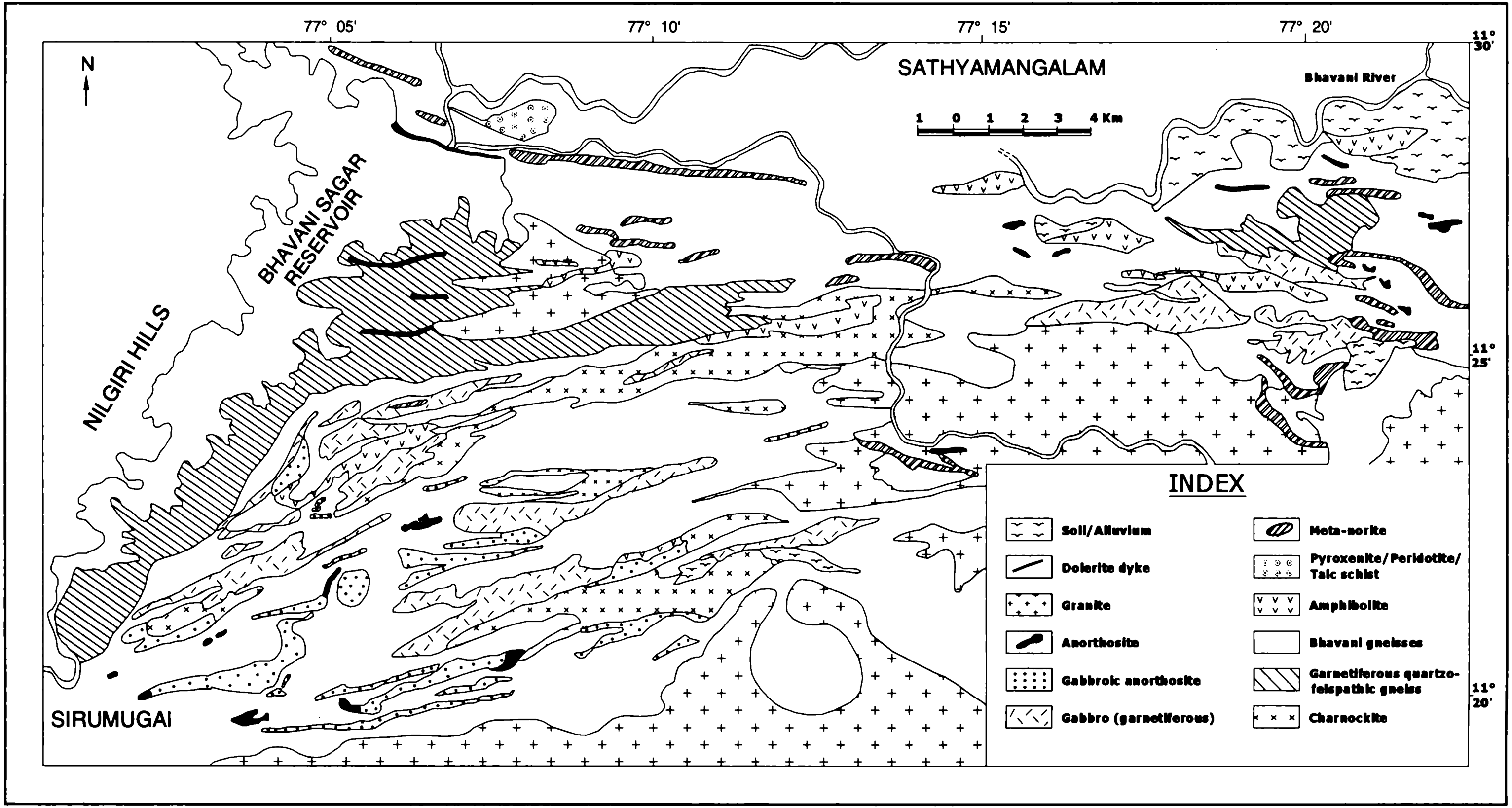

77° 05'
77° 10'
77° 15'
77° 20'
11° 30'
11° 25'
11° 20'
N
SATHYAMANGALAM
Bhavani River
1 0 1 2 3 4 Km
BHAVANI SAGAR RESERVOIR
NILGIRI HILLS
SIRUMUGAI
INDEX
Soil/Alluvium
Dolerite dyke
Granite
Anorthosite
Gabbroic anorthosite
Gabbro (garnetiferous)
Meta-norite
Pyroxenite/Peridotite/Talc schist
Amphibolite
Bhavani gneisses
Garnetiferous quartzo-felspathic gneiss
Charnockite

**Fig.4P-6.** Bhavani layered complex, Tamil Nadu (after Subramanian and Selvan, 2001, p.52).

setting of Bhavani intrusion are very similar to that of Sittampundi complex. Bhavani complex is probably derived from shallow level fractionation of alumina-rich tholeiite magma. Sm-Nd whole rock isochron yields the age of 2898±52 Ma that corresponds to the age of Sittampundi complex (Bhaskar Rao et al. 1996). This age is similar to the ~3000 Ma old ultramafic-mafic-anorthosite intrusions in the Hole Narasipura schist belt (Sargur Group) in WDC. The Sittampundi and Bhavani layered complexes, now dismembered, are probably part of large single intrusion, involved in the intense deformation and high-grade metamorphism of the Marginal Zone. They were regarded as part of Sathyamangalam Group in earlier literature, but may be better correlated with Salem (Tiruvannamalai) Group, with which they are in strike continuity. These layered complexes are variously interpreted as ophiolites or fractionated residues of Andean-type batholiths or merely intrusions at the continental margin.

### Madurai Block

Madurai Block is sandwiched between the Palghat-Cauvery shear zone in the north and the Achankovil shear zone in the south. This block is divided into three different sectors, for the sake of convenience of description (*see* Gopalakrishnan, 2001), as (i) Amaravathi sector (AM), (ii) Kodaikanal-Anaimalai sector (KA) and (iii) Tiruchi-Tirunelveli sector (TT) (Fig.4P-7).

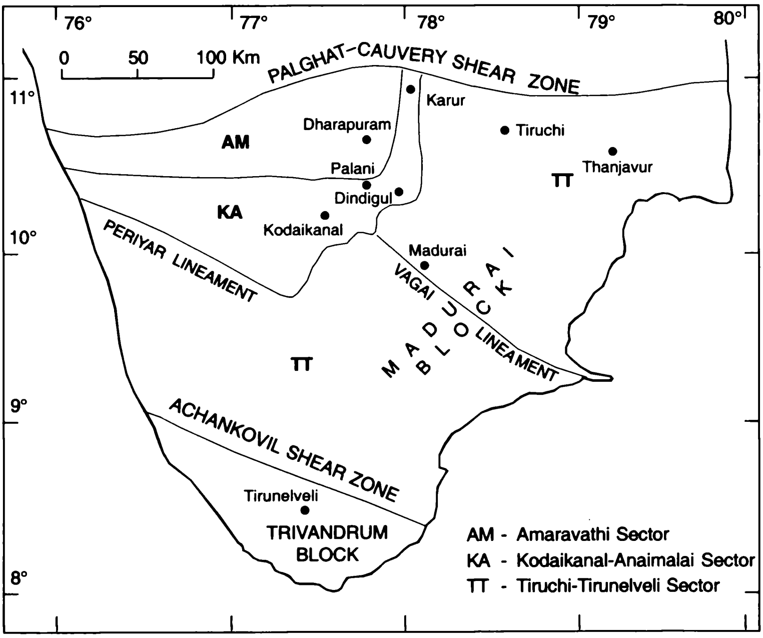

76°
77°
78°
79°
80°
11°
10°
9°
8°
0 50 100 Km
PALGHAT-CAUVERY SHEAR ZONE
Karur
Dharapuram
AM
Tiruchi
Thanjavur
TT
Palani
Dindigul
KA
Kodaikanal
PERIYAR LINEAMENT
Madurai
VAGAI LINEAMENT
TT
ACHANKOVIL SHEAR ZONE
Tirunelveli
TRIVANDRUM BLOCK
AM - Amaravathi Sector
KA - Kodaikanal-Anaimalai Sector
TT - Tiruchi-Tirunelveli Sector

**Fig.4P-7.** Different sectors (terranes) of PMB (after Gopalakrishnan, 2001).

*Amaravathi sector:* It is named after Amaravati River flowing around Dharapuram and consists essentially of enderbitic charnockites (20%) and hornblende-biotite gneisses (60%). Pyroxene granulites and ultramafics (5%) occur as lenses within charnockites and gneisses. Garnet-sillimanite gneisses, calc-silicate rocks and rare quartzites, besides pink granitic gneiss occupy the rest of the area (15%).

An important outcrop is the Madukkarai crystalline limestone (Fig.4P-8a), which supports a cement factory in the area. Calc-silicate rocks and garnet-sillimanite gneisses are associated with these crystalline limestones. The Madukkarai (Sugunapuram) outcrop was correlated with Sathyamanagalam Group earlier, but the recent Sm-Nd garnet whole rock age of 560±17 Ma of sillimanite-garnet schist shows its Pan-African rather than Sargur affinity (Meissner et al. 2002), which is consistent with its belonging to Madurai Block. ENE trending macroscopic folds in this sector belong to the second generation ($F_2$) that have coaxially folded the $F_1$ isoclinal folds on stratification. The Madukkarai outcrop extends west to the Walayar area where the limestone is mined for cement at Pandarettu. The Madukkarai-Walayar band is similar in geological setting to the Manapparai band (Karur Palayam and Sarkar Valavandi outcrops) situated in the east near Karur. Similar bands of crystalline limestone are noticed to the south of Ottapalam near Gayatri River in Kerala.

*Kodaikanal-Anaimalai sector* is mainly composed of pink migmatitic gneisses containing enclaves of ultramafic and mafic rocks. Quartzite-carbonate-pelite (QCP) suite occurs in the Vaigai lowlands. Sapphirine-orthopyroxene granulites are seen near Perumalmalai, Panrimalai, Ganguvarpatti and Kiranur. Cordierite-garnet-spinel rocks are also found in the vicinity. The Palani, Cardamom and Kodaikanal hills and the area around Trichur (Thrissur) in Kerala are formed of charnockites. Anaimalai hills are made of orthogneisses, which show vestiges of recumbent folding. Regional structural trends swerve from WNW to ENE and NE, and finally become N-S in the region between Dindigal (Dindukal) and Karur.

*Tiruchirapalli (Tiruchi)-Tirunelveli (TT) sector* is the most extensive sector in the Madurai Block, and extends across the Periyar and Achankovil lineaments in Kerala. Regional structure of this sector is highly complex with numerous domes and basins resulting from fold interference as in Sirumalai Hills to the east of Dindigul. The TT sector exposes large volumes of quartzite-carbonate-pelite (QCP) suite (~35%) that are classified into Khondalite Group. Although not stratigraphically equivalent of the Khondalite Group of EGMB, the entrenched terminology is continued here until a consensus emerges on new terminology. In less deformed areas, the quartzites preserve ripple marks, as in

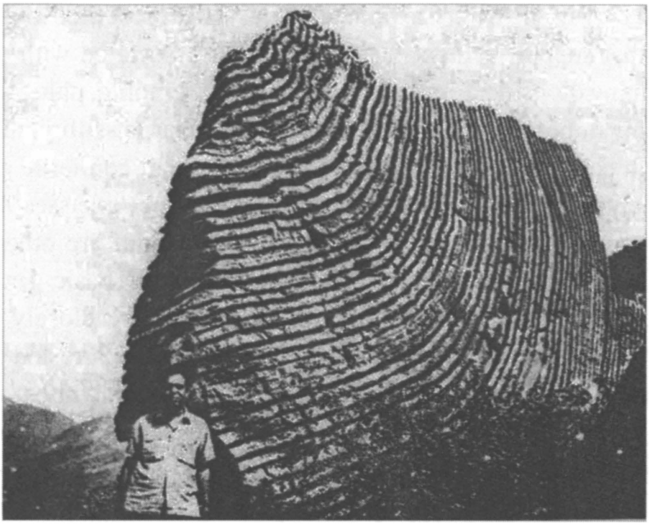


**Fig.4P-8a.** Ribbed and grooved calc-silicate rock, Madukkarai (Subramanian and Selvan, 2001, p.43).

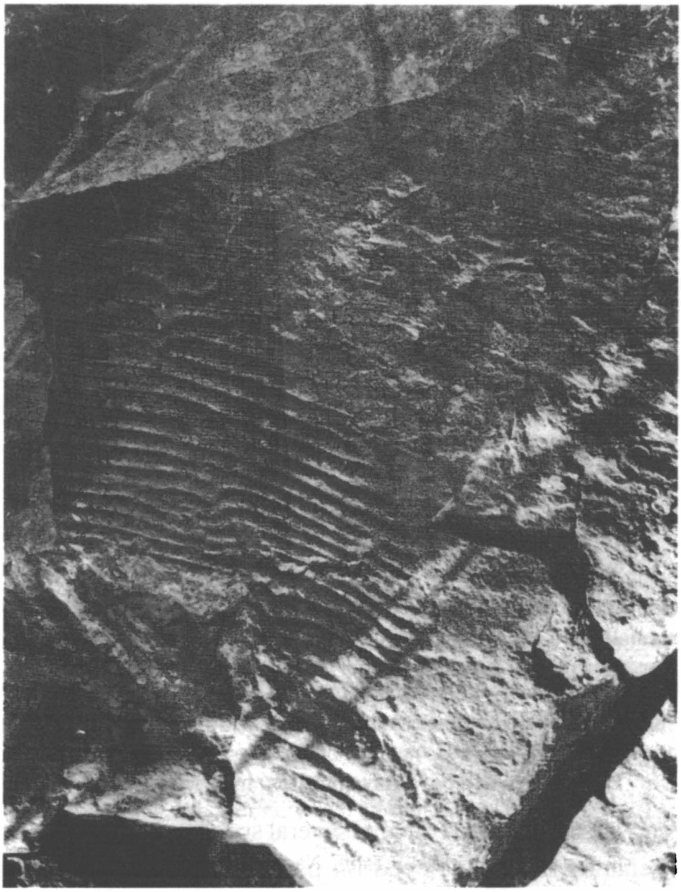


**Fig.4P-8b.** Ripple marks in quartzite, Alagar Malai (Subramanian and Selvan, 2001, p.42).

Alagar Malai (Fig.4P-8b). Carbonate facies is represented by crystalline limestones that support cement factories and are associated with calc-silicate rocks containing diopside, forsterite, wollastonite, tremolite, phlogopite, spinel, humite group minerals, scapolite and graphite. Garnet-sillimanite-graphite gneisses with economic pockets of graphite and garnet-cordierite gneisses are important pelitic rocks of this sector. Cordierite-spinel gneisses in Kambam valley and sapphirine-kornerupine gneisses of Andipatti are other important varieties. The QCP suite contains minor interbands of basic granulites and amphibolites. Charnockites containing diopside are also closely associated. Charnockites also occur as prograde patches of incipient or arrested charnockite within garnet bearing quartzofelspathic paragneisses (leptynites) near Melur (close to Madurai), Papanasam in Tirunelveli District and within hornblende-biotite orthogneisses of Nartamalai near Pudukkottai. Charnockites are also seen as xenolithic lenses within migmatitic gneisses. QCP suite occurs as bands and lenses within charnockite massifs.

### Trivandrum Block

This block is a WNW-ESE trending prominent straight belt in strong contrast to the swirling patterns of Madurai Block. This straight belt is called as Kerala Khondalite belt by some authors due to the abundance khondalite (garnet-sillimanite-graphite gneiss) in the belt. The essential rock types of the belt are garnet-sillimanite-graphite gneisses, garnet-cordierite gneisses, garnet-biotite gneisses, and garnet bearing quartzofelspathic gneisses interlayered with charnockites. Marbles and calc-silicate rocks are common in some areas and quartzites are less abundant than in the Madurai Block.

The Trivandrum Block is subdivided into two sectors or units called the Ponmudi Sub-block and Nagercoil Sub-block. Ponmudi Sub-block consists of an interlayered sequence of garnet-sillimanite-graphite gneisses, garnet-biotite gneisses, garnet-cordierite gneisses, garnetiferous quartzofelspathic gneisses and rare carbonates. The unit is free from mafic-ultramafic association. Regional foliation and banding trends WNW with steep dips towards SW. Isoclinal folds are seen on various scales with the fold axial traces remaining parallel to regional foliation. Nagercoil Sub-block consists mainly of charnockites and gneisses containing several layered anorthositic to noritic bodies.

### Incipient Charnockites in PMB

The Pandyan mobile belt contains several spectacular examples of arrested or incipient charnockites developed on paragneisses (Fig.4P-9a) in contrast to the type area of Kabbaldurga where incipient charnockites are developed

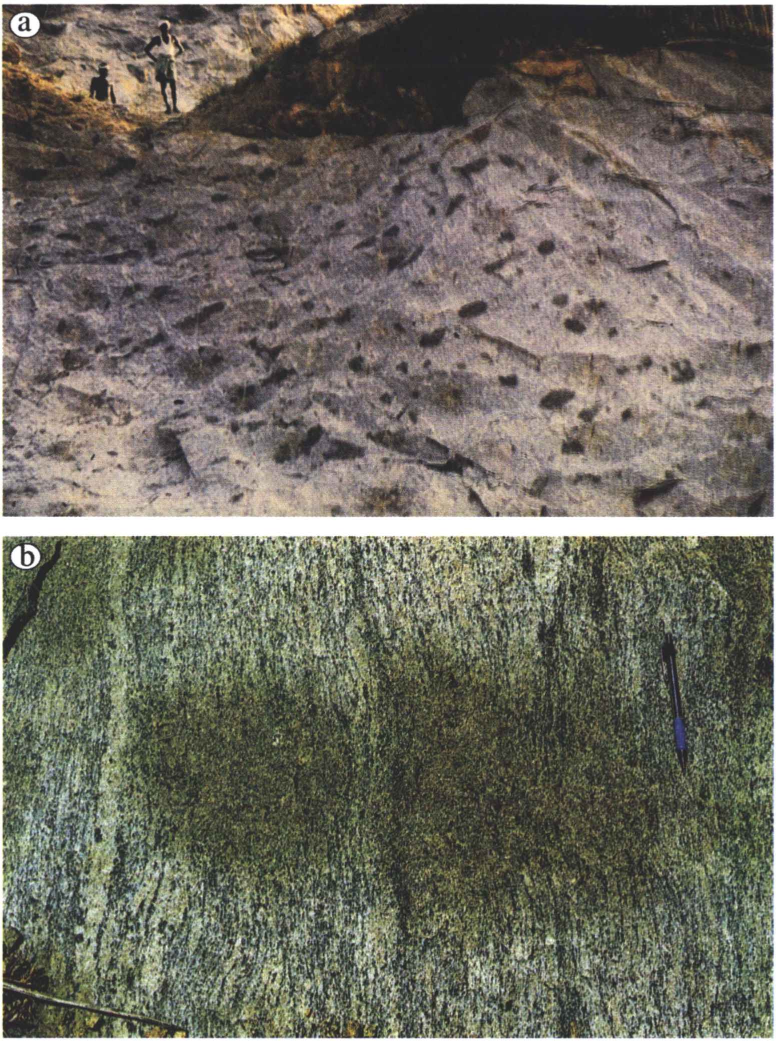


**Fig.4P-9.** (**a**) Arrested charnockite derived from leptynite at Kottavattom near Punalur (from Srikantappa et al. 1985). (**b**) A typical view of patchy charnockite development within hornblende-biotite gneiss at Tolanur near Attingal. The gneiss here is less migmatised, homogeneous and trondhjemitic. Patchy charnockite development in the quarry is discreet and is not obviously linked to any weak deformational planes (after Ravindra Kumar and Venkatesh Raghavan, 1992).

from biotite-hornblende orthogneisses. The common paragneisses are garnetiferous quartzofelspathic gneisses called leptynites. They were first identified from Ponmudi (Ravindra Kumar et al. 1985) and found later at several localities in Trivandrum Block (Mannanthala, Kottavattom, Nulliyam etc) and Madurai Block (Melur, Papanasam, Pudukottai etc). Incipient or arrested charnockite developed from hornblende-biotite orthogneisses (Fig.4P-9b) are also seen in Nemmara, Kodakkad etc. near Palghat (Palakkad) in the

Marginal Zone and near Pudukkottai in Madurai Block. Unlike in Dharwar craton where incipient charnockites are developed along the zone of transition from regional amphibolite to granulite facies, in Pandyan mobile belt, incipient charnockites coexist with quartzofelspathic gneisses irrespective of regional metamorphic zonation. Petrological studies have shown that the orthopyroxene in the incipient charnockite develops by the breakdown reaction of biotite+quartz (±garnet). Recent thermobarometric and fluid inclusion studies have shown that arrested charnockites occurring as patches develop through carbonic metamorphism. This results either from infiltration by $CO_2$ fluids from mantle, or anatexis of crustal carbonates, or due to drop in $H_2O$ pressure during regional metamorphism, or due to reaction of graphite with biotite. Alternately, the incipient charnockites are believed to have formed by dehydration melting of hydrous minerals like hornblende and biotite in the host gneisses during high-grade metamorphism and anatexis. The arrested charnockite development is widely recorded in the Gondwanic neighbours of Sri Lanka and Antarctica.

### Metamorphism

In recent years, pressure-temperature-time (P-T-t) paths have been determined through thermobarometric, micro-textural, isotopic, fluid inclusion and Laser Raman spectral studies of appropriate mineral assemblages in suitable rocks to unravel the metamorphic evolution and history of crustal development of a terrain. The shape and style of P-T-t paths are significant in distinguishing the tectonic processes causing the regional metamorphism. Mainly two types of P-T-t paths are distinguished (Harley, 1989) namely, isothermal decompression (ITD) or isobaric cooling (IBC). The P-T-t loops may be clockwise or counter clockwise (anticlockwise). In clockwise P-T-t paths, maximum pressure is attained before thermal maxima. These are related to plate collision producing medium to high-pressure metamorphism on a thickened crust. The counter clockwise P-T-t paths characterise low P, high T metamorphism where thermal maxima are attained prior to peak pressure conditions. In nature, the P-T-t paths are often complex and may represent a combination of both ITD and IBC paths in a single cycle or in multiple cycles. The Pandyan mobile belt has been extensively studied for its metamorphic evolution.

In Madurai Block, a clockwise ITD path has been determined from textural evidences such as kyanite pseudomorphed by sillimanite, coexistence of staurolite and kyanite and presence of gedrite blebs in orthopyroxene. Geothermobarometry indicates a metamorphic peak at 800°C / 8 kbar, which shows substantial decompression at 700°C / 4-5 kbar. The decompressive event is correlated with Pan-African metamorphism and exhumation around 500-600 Ma. UTH metamorphism is widely reported from Madurai Block (*see* Tateishi et al. 2004). Anticlockwise evolution of UTH assemblages at high pressures (>10 kb) is also suggested from near the collision zone (Santosh and Sajeev, 2006). Palaeoproterozoic (1700-2100 Ma) Sm-Nd model ages and Neoproterozoic (850-950 Ma and 1400 Ma) U-Pb ages of zircon, monazite and titanite, probably indicating the ages of the protoliths and high grade metamorphism, are recorded from many areas.

In Trivandrum Block, textural studies show cordierite development as symplectites and coronas over garnet and spinel, resulting from breakdown of garnet to produce cordierite, spinel and hypersthene. Metamorphic studies show peak conditions at 700-800°C at 6-7 kbar and a decompressive ITD peak at 700°C at 5-6 kbar. Piezothermic array is interpreted as T-convex. UHT (ultrahigh temperature) metamorphism of ~1000°C is recorded through carbon isotope studies of calcite- graphite pair from the marbles of Trivandrum Block. UHT metamorphism is probably caused by the intrusion of igneous charnockites at depth. Isotope dating in Trivandrum Block indicates Pan-African orogeny at 500-600 Ma as summarised by Shabeer et al. (2004) which is similar to that of Madurai Block. Multichronic Archaean-Palaeoproterozoic ages (3200-1900 Ma) recorded from this block are interpreted as signifying earlier tectonic or igneous events. Integration of P-T paths from Madurai and Trivandrum Blocks establishes a decompressional tectonic regime on a regional scale (Fig.4P-10).

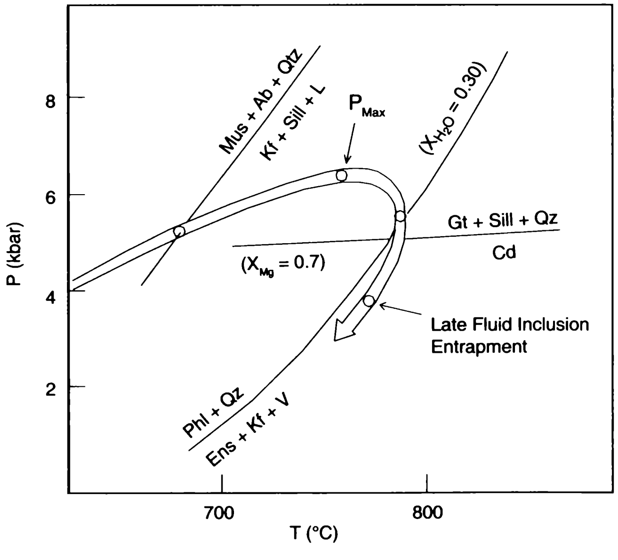


**Fig.4P-10.** Clockwise P-T-t path deduced for KKB (modified from Chacko et al. 1987).

## NEOPROTEROZOIC IGNEOUS INTRUSIONS

### Anorthosite

Proterozoic massive anorthosites form important components of mobile belts in general. They are commonly emplaced at the margins of the belt where QCP successions of shallow water regime dominate. Two prominent intrusions of massive anorthosite intrude the Madurai Block of PMB at Kadavur and Oddanchathram where QCP suite forms the dominant lithology.

*Kadavur Anorthosite* (Fig 4P-11a): Kadavur anorthosite (Subramaniam, 1956b; Sarkar and Bose, 1987) occurring near Tiruchirapalli is of limited aerial extent (70 km$^2$) and consists essentially of anorthosite and gabbro with minor ultramafics, and associated with cogenetic rapakivi granite. It is a composite intrusion involving multiple magmatic pulses. An early cumulate sequence contains anorthosite, leucogabbro and ferrogabbro. The younger cumulate unit overlies the older anorthosite with an unconformity marked by gabbro-norite. Mafic rocks rich in opaque oxides and ferrodiorite dykes intrude the cumulate sequence. Rapakivi granite occurs along the southern margin of the intrusion.

The rocks are folded in three phases, the earliest (F$_1$) representing reclined folds of rootless 'intrafolial type'. The prominent F$_2$ isoclinal folds are nearly coaxial with F$_1$; and F$_3$ are broad open folds. The anorthosite intrusion is late

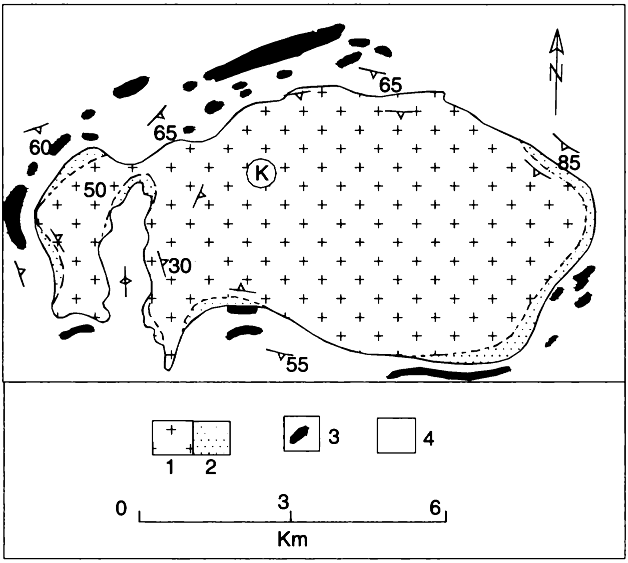


**Fig.4P-11a.** Schematic map of the Kadavur anorthosite. *Index:* **1** - Coarse-grained rocks of the complex; **2** - Fine grained marginal (basal) zone; **3** - Gabbronorite sills in host rocks; **4** - Supracrustal rocks (mostly quartzites and quartz schists); K - Kadavur (after Sarkar and Bose, 1987).

tectonic with respect to $F_2$. Post-emplacement deformation and metamorphism during $F_3$ is noticeable. The country rocks show the effects of thermal metamorphism near the intrusive contacts. Geochemical studies indicate iron enrichment during fractionation from the parental high-alumina tholeiitic magma. Kadavur anorthosite has characteristics that are intermediate between layered complexes and massif anorthosites, although it is broadly classified as a massif type anorthosite.

*Oddanchathram Anorthosite* (Fig.4P-11b): This intrusion located near Palani and trending NE for 16 km is a typical Proterozoic-type massive anorthosite containing 90% plagioclase ($An_{51-59}$) associated with lenses of Fe-Ti oxides. The important mafic minerals are hornblende, augite, orthopyroxene and locally garnet. The anorthosite is coarse grained in the centre and fine grained at the periphery. It has clear intrusive contacts with the surrounding charnockite and QCP rocks, and contains country rock xenoliths in the contact zone. Geothermometric studies have indicated temperatures of intrusion of about 700-900°C, but the pressures determined are highly variable. There is an opinion that the emplacement of anorthosite occurred in two phases, the early norite and gabbroic anorthosite followed by the anorthosite proper. The anorthosite is recently dated by SHRIMP U-Pb of zircon at ~560 Ma.

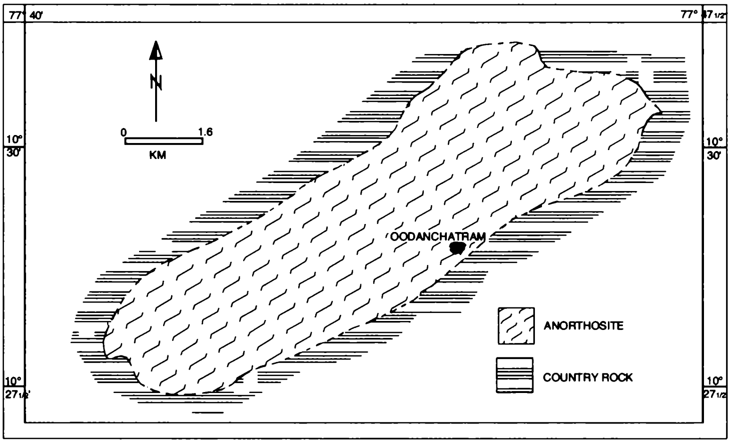


**Fig.4P-11b.** Geological map of the Oddanchatram anorthosite, Maduari District, Tamil Nadu (from Janardhan and Wiebe, 1985).

*Perinthatta Anorthosite:* Perinthatha anorthosite is a prominent non-layered intrusion in the Bavali shear zone (extension of Moyar shear zone in Kerala) that consists essentially of anorthosite with dioritic variants and titanomagnetite bands. The anorthosite body is emplaced within charnockites, gneisses and Wayanad schist belt which is extension of Sargur belt.

### Basic and Ultrabasic Intrusions

Gabbro bodies are emplaced along the Bavali shear zone at Kartikulam, Adakkanthodu and Karrang. A gabbroic anorthosite body is reported at Kotagiri in Nilgiri Hills. Minor bodies of peridotite and pyroxenite occur in the Transition Zone of PMB in Attappadi and other places in Kerala. Kakkapponnu ultramafic body in Achankovil Shear zone consists of dunite, glimmerite and spinellite derived from highly potassic, $CO_2$ rich melts (Rajesh et al. 2004).

*Ezhimala Gabbro-Granophyre:* This is NNW-trending small intrusion (6x3 km) emplaced in the Wayanad schist belt along the Bavali shear zone. The intrusion is described as gabbro-granophyre-granite or gabbro-tonalite-granite suite. Rb-Sr age of ~680 Ma is reported for the granite-granophyre.

### Alkali Plutons

Alkaline magmatism is associated with continental rifts or regions affected by post-orogenic extensional collapse. The PMB has an array of alkali plutons, over 30 in number, ranging from alkali granites and syenites, nepheline syenites, carbonatites and alkali pyroxenites and gabbros. These intrusions are mainly associated with regional lineaments and fracture zones, and are generally undeformed and therefore anorogenic. These are generally small (5-40 sq.km) elliptical bodies having sharp contacts with the host gneisses and charnockites. They are mainly Neoproterozoic intrusions (550-750 Ma), largely confined to NW and NE lineaments that are related to the break-up of the continental margins. The fracture zones containing the alkali plutons extend from the PMB to the borders of Dharwar craton. The alkali intrusions, carbonatites and kimberlites of the craton have been described in Chapters 3 and 5.

*Sivamalai Syenite* (Fig. 4P-12): Among the important alkali plutons is the Sivamalai syenite, which has Rb-Sr age of 623±21 Ma and U-Pb TIMS zircon age of 590 Ma (Upadhyay et al. 2006). This pluton consists of a variety of syenites like the aegirine augite-, augite-, zircon-, and corundum-syenites, as well as nepheline- and other felspathoid-syenites. Pegmatoidal veins of nepheline syenite are seen in western part of the pluton. At the contact with the surrounding rocks, the syenite body has developed feeble banding. Nepheline syenite contains schlieren of mafic alkaline rocks. The essential minerals of

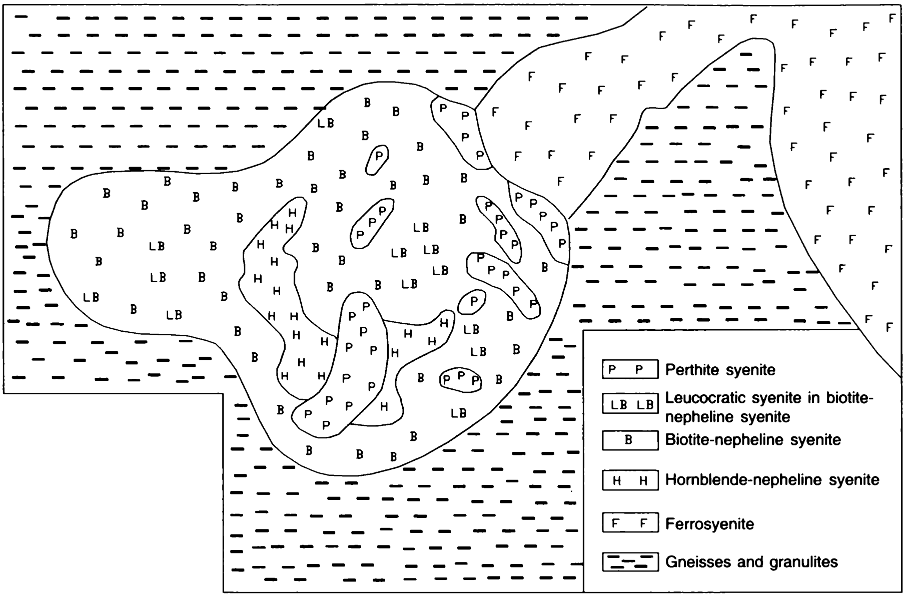

P P Perthite syenite
LB LB Leucocratic syenite in biotite-nepheline syenite
B Biotite-nepheline syenite
H H Hornblende-nepheline syenite
F F Ferrosyenite
Gneisses and granulites

**Fig.4P-12.** Different types of Sivamalai syenite (Bose, 1971, p.242).

the nepheline syenite are albite, mesoperthite, nepheline and other felspathoids, pyroxene, amphibole, zircon, spinel and minor quartz in some varieties. The syenites are mostly miaskitic. They are enriched in Al, Na, Zr and Hf and have low incidence of Fe, Mg, Mn, Li and REE.

*Puttetti syenite:* A small, elongated syenite pluton at Puttetti near Kanyakumari associated with cumulate pyroxenite has U-Pb zircon age of ~570 Ma and Pb-Pb isochron of 508±25 Ma. The syenite abounds in alkali felspar, hedenbergite and phlogopite, shows strong REE fractionation and is probably generated by partial melting of K-rich upper mantle. The syenite gives a K-Ar age of ~450 Ma indicating cooling at ~415° C.

*Mannapra syenite:* This syenite body near Trichur essentially consists of alkali feldspar, two pyroxenes, amphibole, biotite and opaques, with minor quartz and plagioclase. The petrogenesis of Mannapra syenite is similar to that of Puttetti syenite.

*Other syenites:* Other bodies of syenite emplaced along fracture zones in PMB are those near Wadakkancheri, Munnar and Kambamettu. Alkaline rocks in the boundary zones of WDC are Angadimogar, Thaluru, Kumbdaje and Sulliya. Alkaline rocks of Dharmapuri rift and its vicinity are described under the section on Dharwar craton.

*Alkaline Granites:* Alkaline granites of mostly Pan-African age are located in the marginal zone of Pandyan mobile belt at Sankari, Punjaipuliyanpatti, Karamadai, Maruda Malai, Angadimogar, Ambalavayal, Kalpatta and Peralimala. The granites show and age range of 550-600 Ma and contain a leucocratic and a pink phase. Geochemically they have also affinities with the A-type within-plate granite. Some granites have an age bracket of 700-750 Ma that corresponds to the alkaline-carbonatites of Dharmapuri rift. In Kerala too, similar granites are reported at Chengannur, Munnar, Pariyaram, Kizhakkancheri, Athiringal, Pathanapuram, Pathanamthitta and Vellingiri. They generally have granite to adamellite composition, and range in age from 500 to 550 Ma to 700 to 740 Ma and are of A-type. They are commonly associated with fault lineaments. In Munnar, the alkali granite is associated with syenite and carbonatite.

Location of syenites and alkali granites of PMB and its vicinity are given in Fig.4P-13.

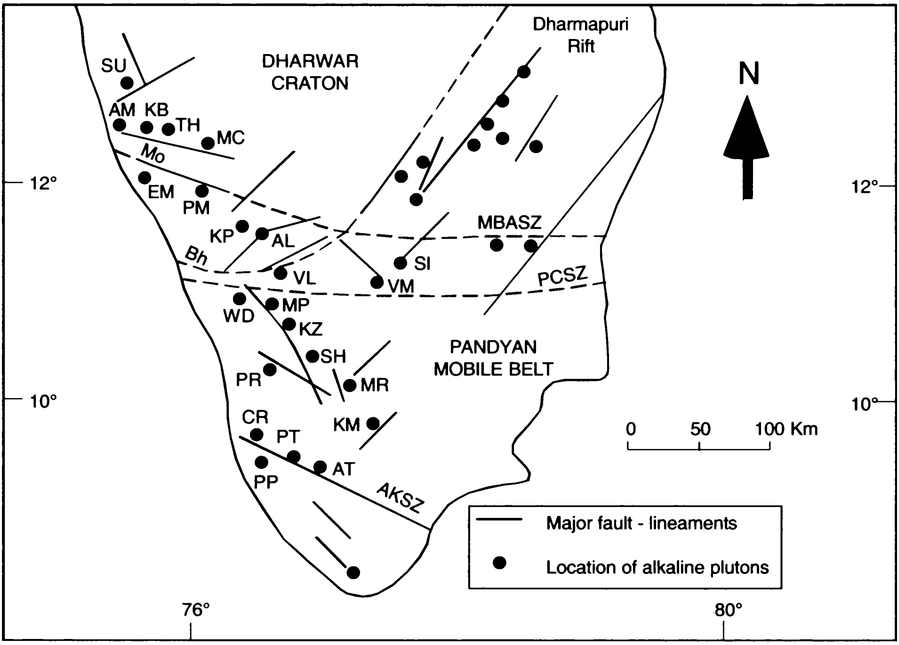

Dharmapuri Rift
DHARWAR CRATON
N
SU
AM KB
TH
MC
Mo
EM
PM
KP
AL
Bh
VL
SI
VM
MBASZ
PCSZ
WD
MP
KZ
SH
PR
MR
PANDYAN MOBILE BELT
CR
PT
KM
AT
PP
AKSZ
12°
10°
76°
80°
0 50 100 Km
Major fault - lineaments
● Location of alkaline plutons

**Fig.4P-13.** Location of alkaline plutons in southern Peninsular India and their spatial relationship to regional fault lineaments (after Rajesh and Santosh, 1996, with permission from Elsevier). Alkaline carbonatite rocks of Dharmapuri rift zone are also shown but described under Dharwar craton (pp.167-169). Mo - Moyar shear zone, Bh - Bhavani shear zone, MBASZ - Moyar-Bhavani-Attur Shear zone, AKSZ - Achankovil shear zone. SU - Sulliya, AM - Angadimogar, KB - Kumbdage, TH - Thaluru, MC - Mercara (Madikeri), EM - Ezhimala, PM - Peralimala, KP - Kalpatta, AL - Ambalavayal, VL - Vellingiri, VM - Vattamalai, SI - Sivamalai, MP - Mannapra, WD - Wadakkancheri, KZ - Kizhakkanchery, SH - Sholayar, MR - Munnar, PR - Pariyaram, KM - Kambamettu, CR - Chengannur, PT - Pathanamthitta, AT - Athiringal, PP - Pathanapuram.

## GEOPHYSICAL STUDIES

Bipolar gravity and magnetic anomalies in the craton-mobile belt boundary suggest continental collision. Gravity modelling has indicated 4-layer crust with Moho depth ranging between 41 and 46 km, and suggested underthrusting of the craton beneath the SGT (Mishra and Vijaya Kumar, 2005). Interpretation of aeromagnetic maps has indicated Moho depth of 36 km below the craton. The magnetic crust is thin, and is confined to 22 km. Wide band magneto-telluric studies have identified crustal blocks separated by shear zones. Anomalously high conducting layer in the upper crust along the PCSZ coincides with the gravity high reported from Palghat Gap. Deep seismic reflection and refraction studies (Fig.4P-14 a, b) across the PCSZ brought out 4-layered

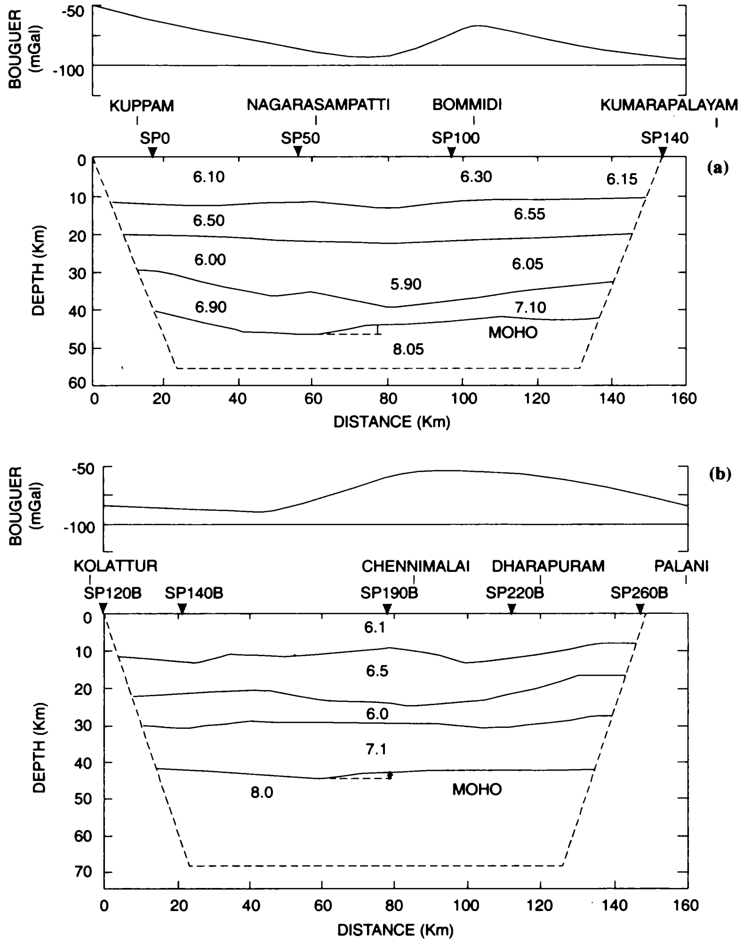


**Fig.4P-14.** **(a)** 2-D velocity structure of the Kuppam-Kumarapalaiyam segment along with gravity profile. **(b)** 2-D velocity structure of the Kolattur-Palani segment with gravity profile (after Reddy et al. 2003). SP - Shot Point on the profile.

velocity structure, with a low velocity zone (7-15 km) in the mid-crust. Seismic reflections show opposing dips probably suggesting collision, but may also suggest a major Dharmapuri rift zone containing abundant alkali-carbonatite association. The crustal thickness varies between 41 and 45 km, with a Moho upwarp of 3-4 km along Dharmapuri rift. A south-dipping Moho was located in the Palghat Gap area, with a Moho upwarp near Chennimalai, supporting collision of PMB with Dharwar craton (*see* Geol Soc. India Mem. no.50, 2003; Gondwana Res., v.10(1&2), 2006).

## TECTONIC EVOLUTION

The presence of QCP suite as the predominant lithological association in PMB and the boundary shear zone (PCSZ) abutting against the Dharwar craton suggests that the origin of Pandyan mobile belt is by the collision of Dharwar craton with another craton in East Gondwana (probably the Congo craton) during Pan-African times. Recent isotopic dating has brought out a series of magmatic, metamorphic and deformational events in PMB, namely, mafic granulites and gneisses of ~2.9 Ga age involved in granulite facies metamorphism of 2.5 Ga in the Marginal zone, granitic activity at ~2.0 Ga followed by metamorphism at 1.6 Ga in PMB, shearing along PCSZ at ~800 Ma, 550 to 600 Ma event of granite emplacement along shear zones, 500-600 Ma event of charnockitisation in PMB and final thermal resetting event in Kerala Khondalite belt at ~480 Ma. The major collisional event may have occurred around 550-600 Ma in a 500-800 Ma time span involving basin formation, folding, shearing, magmatism and granulite metamorphism. MBASZ

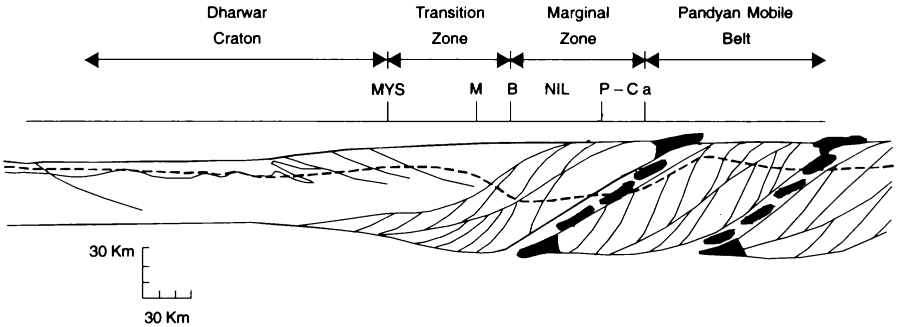


**Fig.4P-15a.** A sketch of crustal section from north to south illustrating a model for late-Archaean crustal shortening and thickening in south India before the development of major transcurrent shear belts. The bold dashed line represents the depth of presently exposed rocks after crustal thickening (modified after Drury et al. 1984; Newton, 1990 and others). Black slabs denote eroded 'ophiolites', Sigmoidal lines mark possible underthrusts. MYS - Mysore; NIL - Nilgiri; M-B - Moyar-Bhavani shear zone. P-Ca - Palghat-Cauvery shear zone.

and PCSZ are described as forming a crustal scale flower structure (Chetty and Bhaskar Rao, 2006).

The earlier tectonic models visualising this terrain as an Archaean fragment underthrusting the Dharwar craton during 2500 Ma to produce regional charnockites parallel to isograds in the craton (Figs.4P-15a and b) have been found to be questionable in the light of dominant Neoproterozoic tectono-thermal events in the Pandyan mobile belt. Another model (Fig 4P-15c)

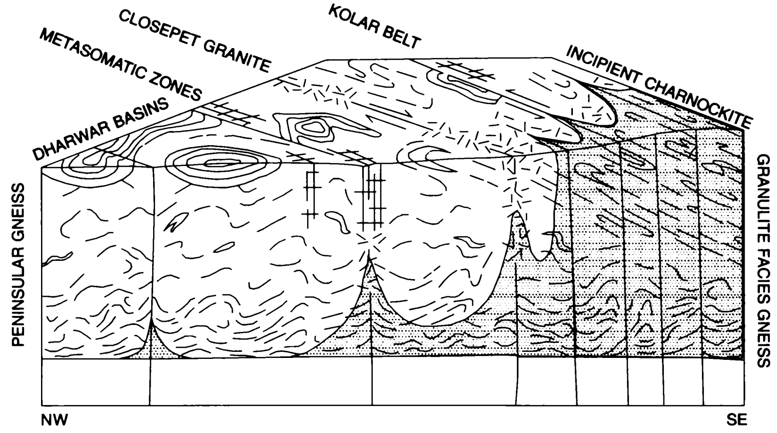

CLOSEPET GRANITE
KOLAR BELT
METASOMATIC ZONES
DHARWAR BASINS
INCIPIENT CHARNOCKITE
PENINSULAR GNEISS
GRANULITE FACIES GNEISS
NW
SE

**Fig.4P-15b.** Cross-section of southern Dharwar craton (modified from Newton, 1990).

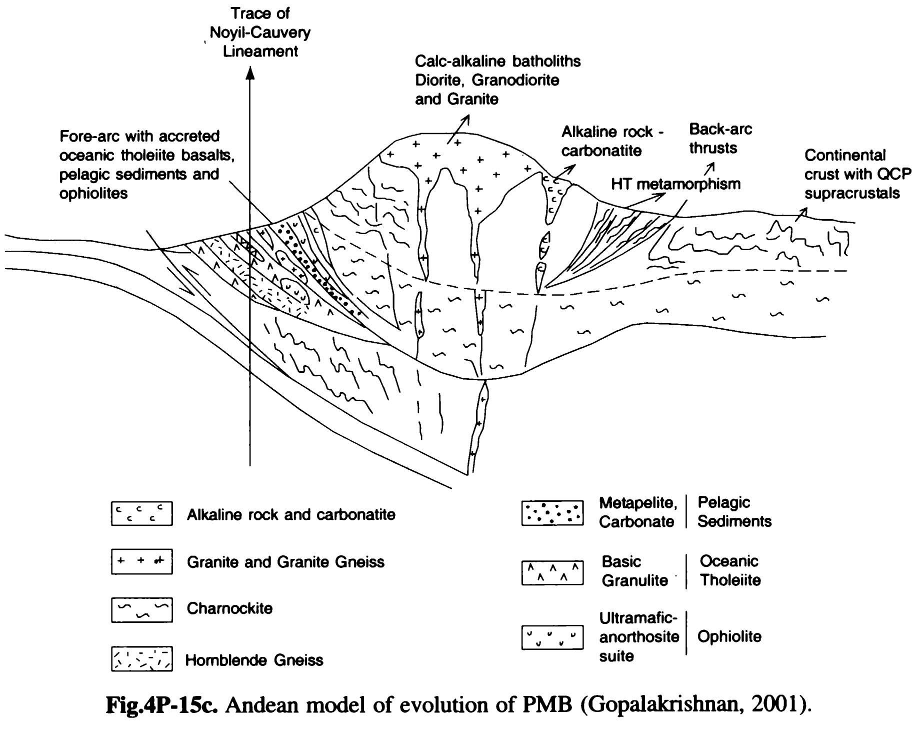

Trace of Noyil-Cauvery Lineament
Calc-alkaline batholiths Diorite, Granodiorite and Granite
Fore-arc with accreted oceanic tholeiite basalts, pelagic sediments and ophiolites
Alkaline rock - carbonatite
Back-arc thrusts
HT metamorphism
Continental crust with QCP supracrustals
Alkaline rock and carbonatite
Granite and Granite Gneiss
Charnockite
Hornblende Gneiss
Metapelite, Carbonate
Pelagic Sediments
Basic Granulite
Oceanic Tholeiite
Ultramafic-anorthosite suite
Ophiolite

**Fig.4P-15c.** Andean model of evolution of PMB (Gopalakrishnan, 2001).

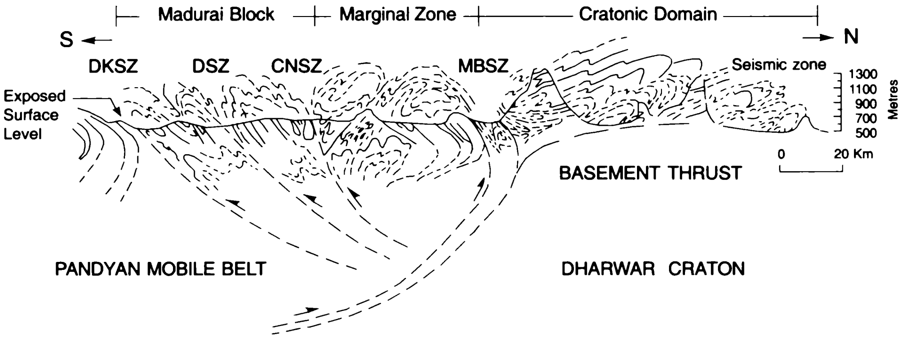

Madurai Block
Marginal Zone
Cratonic Domain
S
N
DKSZ
DSZ
CNSZ
MBSZ
Seismic zone
Exposed Surface Level
1300
1100
900
700
500
Metres
0
20 Km
BASEMENT THRUST
PANDYAN MOBILE BELT
DHARWAR CRATON

**Fig.4P-15d.** Structural cross-section showing overthrusted granulite facies rocks on the Dharwar craton. Shear zones (SZ): MBSZ - Moyar-Bhavani; CNSZ - Chennimalai-Noyil; DSZ - Dharapuram; DKSZ - Devattur-Kallimandayam. Note seismic zone in the craton and the north verging basement thrust (Chetty and Bhaskar Rao, 2006).

visualises an Andean type subduction of oceanic crust from the north beneath Madurai Block to produce the PMB. The crustal scale shear zones are involved in flower structure in accordance with the model of Chetty and Bhaskar Rao (2006) (Fig.4P-15d). Non-collision models visualise continental rifting of Archaean basement, QCP sedimentation and basin inversion by magmatic underplating, resulting in igneous, metamorphic and deformational events to produce PMB (Mahadevan, 1994). The Pandyan mobile belt extends to the neighbours of Madagascar, Sri Lanka and East Antarctica where the regional geology provides a broad match (*see* Braun and Kriegsman, 2003). Details of the best fit will have to be worked out for the supercontinent assembly and their dispersal in Proterozoic to solve this riddle.

Santosh et al. (2009) propose a tectonic model for PMB involving Pacific-type orogeny progressing to collision-type orogeny during late Neoproterozoic-Cambrian. In this model, the PCSZ, marked by ophiolite containing eclogite and UHT assemblages, represents the collisional suture. The suture marks the site where Mozambique Ocean was subducted resulting in the Andean-type magmatic arc of Madurai Block with its TTG suite. This Himalayan-type orogen formed part of the Gondwana supercontinent amalgam.

# SATPURA MOBILE BELT

## INTRODUCTION

Satpura mobile belt or the recently popular name of Central Indian Tectonic Zone (CITZ) for its dominant central part, after Radhakrishna and Ramakrishnan (1988), Radhakrishna (1989) and Acharyya and Roy (2000), is a complex orogenic belt that has amalgamated the southern Deccan Proto-continent with the northern Bundelkhand Proto-continent in the Proterozoic (Fig.4S-1). CITZ is bounded to the north by the Son-Narmada North Fault (SNNF) and to the south by the Central Indian Shear Zone (CISZ). The mobile belt, named after Satpura Hills, is covered for a large part by the Gondwana sediments, Quaternary alluvium and Deccan Trap, and consists mainly of gneisses, supracrustal rocks, granites and boudin-type granulites. The structural trend of gneisses and supracrustals, was known in the early literature as 'Satpura Trend' or 'Satpura Strike'. The extensive gneissic terrain encloses three sub-parallel, E-W trending supracrustal belts, separated from each other by crustal scale ductile shear zones, closely associated with granulite belts consisting of a string of granulite boudins. The supracrustal belts are Mahakoshal belt in the north, Betul belt in the middle and Sausar belt in the south. The granulite belts are the Makrohar belt in the north, Ramakona-Katangi belt in the middle and Balaghat-Bhandara belt in the south. The ductile shear zones are the Son-Narmada South Fault (SNSF) that separates the Mahakoshal and Betul belts, and the Tan Shear Zone (TSZ) that separates the Betul and Sausar belts. Satpura mobile belt links up with the Chhotanagpur Gneiss in the east, continues into Meghalaya plateau, and is presumed to abut against the Indo-Myanmar mobile belt underneath the alluvial cover. In the west, the mobile belt links up with eastern part of the Aravalli craton (called the Mewar craton) and ends up against the Himalayan orogenic belt underneath the Indo-Gangetic alluvium (*see* Fermor, 1936; Yedekar et al. 1990).

The composite Satpura mobile belt was shown as linked with the Eastern Ghat mobile belt (EGMB) around the Singhbhum craton constituting the Middle Proterozoic (1.5-2.0 Ga) Mobile Belt (MPMB), by Radhakrishna and Naqvi (1986). Leelanandam et al. (2006) agreed with this view and called MPMB as the Great Indian Proterozoic Belt. The lithological ensemble of Satpura belt and EGMB are extremely diverse and their mutual difference is further accentuated by the pervasive granulite facies metamorphism of EGMB. The

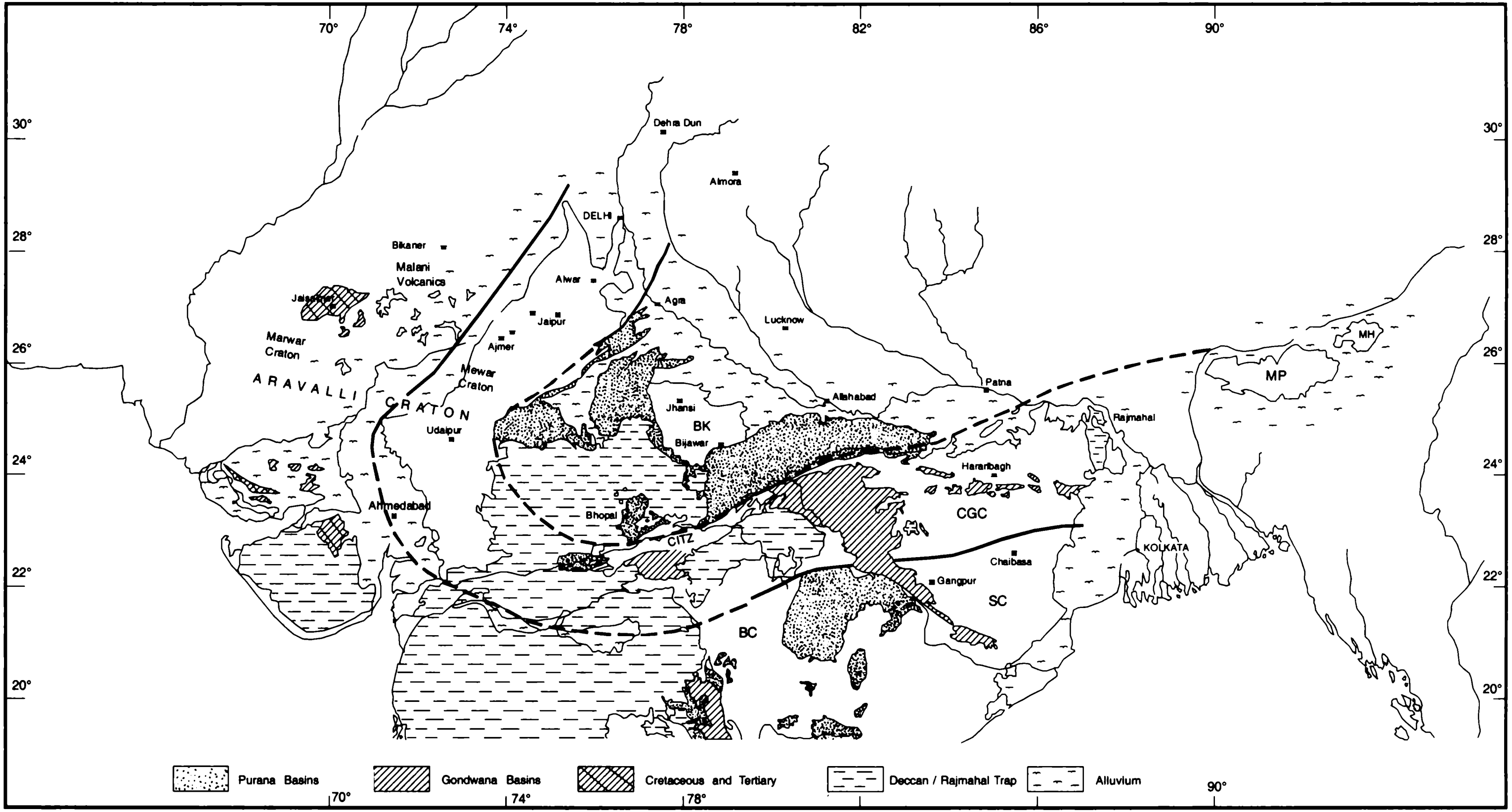

70°
74°
78°
82°
86°
90°
30°
28°
26°
24°
22°
20°
Dehra Dun
Almora
DELHI
Bikaner
Malani Volcanics
Alwar
Agra
Lucknow
Jaisalmer
Jaipur
Ajmer
Marwar Craton
ARAVALLI CRATON
Mewar Craton
Udaipur
Jhansi
BK
Bijawar
Allahabad
Patna
Rajmahal
MP
MH
Hazaribagh
Ahmedabad
Bhopal
CITZ
CGC
Chaibasa
Gangpur
SC
KOLKATA
BC
Purana Basins
Gondwana Basins
Cretaceous and Tertiary
Deccan / Rajmahal Trap
Alluvium

**Fig.4S-1.** Satpura mobile belt, its extensions and adjacent cratons (modified from Fermor, 1936). MP - Meghalaya Plateau; MH - Mikir Hills, CGC - Chhotanagpur Gneiss; CITZ - Central Indian Tectonic Zone; BC - Bastar Craton; SC - Singhbhum Craton, BK - Bundelkhand Craton.

presumed link between the Satpura belt and EGMB underneath the alluvium in the east of Singhbhum craton is also conjectural. Realising these critical differences, Radhakrishna and Ramakrishnan (1988) and Radhakrishna (1989) recognised that Satpura belt and EGMB are separate, unconnected mobile belts whose extensions are respectively found in Western Australia (Harris, 1993) and Eastern Antarctica (Crawford, 1974). The importance of this composite Satpura orogenic belt lies in its vast extent and complex geology that have spawned a variety of tectonic models. These models explain the assembly of the two proto-continents of Indian shield within the framework of the global Proterozoic supercontinents.

### Previous Studies

The broad geological framework of Satpura mobile belt was established through the pioneering work of H.B. Medlicott in 1869, W.T. Blanford in 1869, P.N. Bose in 1884, J.B. Auden in 1933, H. Crookshank in 1936 and W.D. West in 1962. Geological Survey of India initiated the first major revision of regional geology in 1978 through the multi-disciplinary "PROJECT CRUMANSONATA" ("Crust-Mantle Studies along Son-Narmada and Tapti Lineaments") and the synthesis of results appeared in Special Publication 10 of GSI (*see* Jain et al. 1995). Summaries of geological results appeared earlier (Yedekar et al. 1990) along with geophysical interpretation (Nayak et al. 1990). Modern interpretation of CITZ in plate tectonic terms has emerged in recent years (Acharyya and Roy, 2000; Roy et al. 2000; Roy and Hanuma Prasad, 2001, 2003; Acharyya, 2001, 2003). Edited volumes periodically updating the studies till date are GSI (1981, 1990, 2000, 2001, 2004a), Sinha-Roy and Gupta (1995), PROJECT CRUMANSONATA (1995) and Roy and Mohabey (2003).

## CENTRAL INDIAN TECTONIC ZONE (CITZ)

A generalised cross section of the CITZ is given in Table 4S-1 for providing a tentative synoptic picture of the mobile belt (Fig.4S-2). Descriptions of the various units of CITZ are given below:

### Son-Narmada North Fault (SNNF)

The SNNF extends all along the outer periphery of the Vindhyan basin, and has been active until Neoproterzoic, causing the downthrow of the basin to the north. This fault marks the northern boundary of the Mahakoshal belt as well as the northern boundary of the CITZ. SNNF has been dormant since Proterozoic as evidenced by the overlap of Gondwana sediments onto the Vindhyan sediments near Katni.

**Table 4S-1.** North-South tabular cross section of CITZ

| | |
|---|---|
| | Vindhyan and Bijawar Basins and Gneissic Slivers (e.g. Sidhi) (Bundelkhand craton) |
| | - - -Son-Narmada North Fault - - - |
| C | Mahakoshal Group |
| | - - -Son-Narmada South Fault - - - |
| I | - - -Makrohar Granulite Belt - - - - |
| | - - -Balrampur Fault- - - - |
| | Betul Group |
| | - - -Tan Shear Zone - - - - |
| T | - - -Ramakona-Katangi Granulite Belt- - - |
| | Sausar Group |
| Z | - - - Balaghat-Bhandara Granulite Belt- - - |
| | - - - Central Indian Shear Zone - - - - |
| | Sakoli and Chilpi Belts and Gneisses (Bastar craton) |

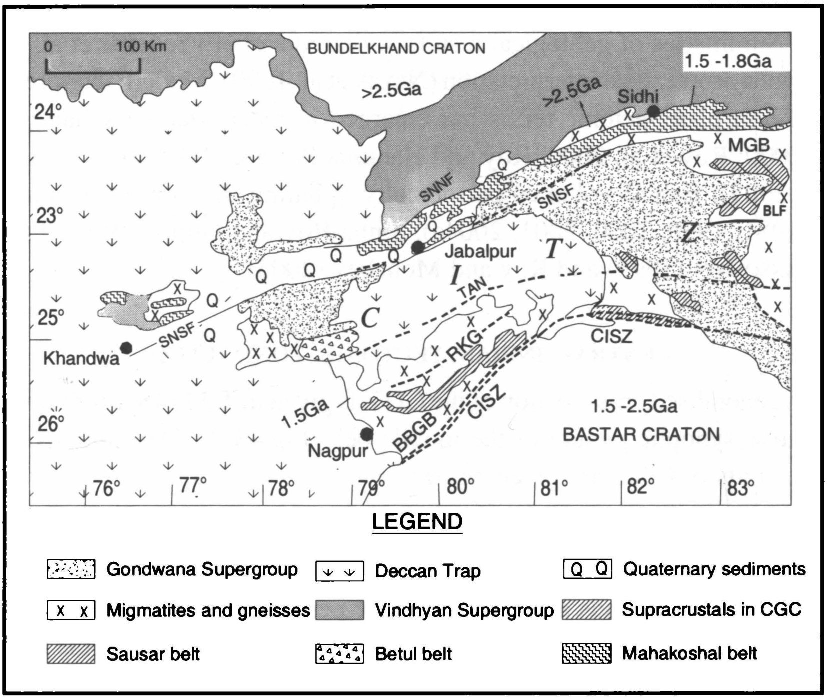

0 100 Km
BUNDELKHAND CRATON
>2.5Ga
>2.5Ga
1.5 -1.8Ga
Sidhi
MGB
BLF
SNNF
SNSF
Jabalpur
T
I
C
Z
TAN
RKG
CISZ
BBGB
Khandwa
SNSF
Nagpur
1.5Ga
1.5 -2.5Ga
BASTAR CRATON
Q
X
24°
23°
25°
26°
76°
77°
78°
79°
80°
81°
82°
83°
LEGEND
Gondwana Supergroup
Deccan Trap
Quaternary sediments
Migmatites and gneisses
Vindhyan Supergroup
Supracrustals in CGC
Sausar belt
Betul belt
Mahakoshal belt

**Fig.4S-2.** Geological map of the CITZ (after Roy et al. 2002). **SNNF** - Son-Narmada North Fault, **SNSF** - Son-Narmada South Fault, **MGB** - Makrohar Granulite Belt, **TAN** - Tan Shear Zone, **RKG** - Ramakona-Katangi Granulite Belt, BBGB - Balaghat-Bhandara Granulite Belt, **CISZ** - Central Indian Shear Zone, **BLF** - Balrampur Fault.

## Mahakoshal Supracrustal Belt

The ENE-WSW trending Mahakoshal belt (Fig.4S-3) extends for about 600 km from Barmanghat (Narsinghpur) to Rihand Dam (Govind Ballabh Pant Sagar) with a maximum width of about 20 km and covers an area of about 9000 km$^2$. The belt also includes the Harda Inlier in the west. The Mahakoshal belt has its northern boundary marked by Son-Narmada North Fault (SNNF) and the southern boundary by the Son-Narmada South Fault (SNSF), and these faults together constitute the Son-Narmada (SONA) fault system. SNNF separates the Mahakoshal belt from the Proterozoic Vindhyan basin in the north, with intervening local slivers of Sidhi gneiss, which is regarded as the equivalent of Bundelkhand granite. SNSF separates Mahakoshal belt from a vast expanse of Proterozoic granites and gneisses of CITZ, and is covered for the most part by Deccan Trap, Gondwana sediments and Quaternary alluvium.

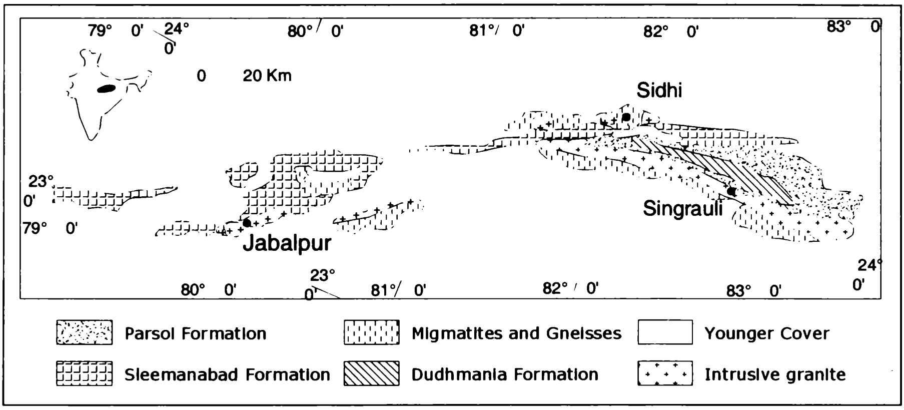


**Fig.4S-3.** Geological map of Mahakoshal supracrustal belt (after Roy and Devarajan, 2000).

The main rock types of Mahakoshal belt are quartzite, carbonate, chert, BIF, greywacke-argillite and mafic volcanics. Some authors therefore called the Mahakoshal belt as a greenstone belt, although the term is not appropriate as the belt has predominant sediments rather than basic volcanics or greenstones. In view of its lithologic similarity with the undeformed Bijawar basin of Bundelkhand craton in the north, H.B. Medlicott in 1869 correlated it with the Bijawar Group. Due to differences in deformation and metamorphism from the type Bijawar basin, R.D. Oldham and co-workers in 1901 called it the "Transition Series", but Auden (1933) described it as the 'Bijawar of Narmada Valley', and this view prevailed for a long time. Later geological work by Akhilesh Narain and P.I. Thambi of GSI in 1978 brought out critical differences between the type Bijawar basin and the supracrustal rocks of Narmada valley. These authors therefore named the Bijawar of Son Valley as Mahakoshal belt

**Table 4S-2.** Lithostratigraphy of Mahakoshal Group

<table>
<tr><td colspan="3">Quartz porphyry, albite granite, syenite, lamprophyre, dolerite, peridotite/dunite<br>Granitoids (Barambaba, Jhirgadandi, Madanmahal, Tamakhan)</td></tr>
<tr><td></td><td></td><td>Other Nomenclature</td></tr>
<tr><td>Dudhamaniya Formation</td><td>Alternating sequence of BIF and phyllite</td><td>Parsoi Fm.</td></tr>
<tr><td></td><td>------- Gradational Contact -------</td><td></td></tr>
<tr><td>Parsoi Formation</td><td>Greywacke-argillite, carbonaceous phyllite, felspathic quartzite and basal polymict conglomerate</td><td>Parsoi Fm.</td></tr>
<tr><td></td><td>----- Faulted Contact/ Unconformity ---- -</td><td></td></tr>
<tr><td>Sleemanabad Formation</td><td>Pillowed basalt, manganiferous chert, BIF and ultramafic plugs</td><td>Chitrangi Fm.</td></tr>
<tr><td></td><td>Quartz arenite, stromatolitic carbonate, BIF and phyllite</td><td>Agori Fm.</td></tr>
<tr><td></td><td>------- Unconformity -------</td><td></td></tr>
<tr><td></td><td>Sidhi gneiss and Dudhi granitoids with enclaves of supracrustal rocks</td><td></td></tr>
</table>

Fm.=Formation

after the historic name of the geographic region. Nair et al. (1995) worked out the stratigraphy of the belt modifying the earlier works of S.M. Mathur, V.D. Choubey and many others. After recent geological mapping by M.K. Devarajan and others, the stratigraphy of the belt was revised by Roy and Devarajan (2000), who also provide a historical review of previous work. Their classification is presented in Table 4S-2. The essential difference among the different classifications is in the nature of the base, like volcanic rocks in some and the shelf sequence of arenite-carbonate-BIF in the others. Further, the Parsoi Formation is subdivided in the present classification into BIF-dominated sequence at the top and the clastic sequence below it (Table 4S-2).

### *Description of Lithology*

*Basement Gneisses:* The basement gneisses occur as a lenticular strip from Sidhi to Bansagar between Mahakoshal Group in the south and the Vindhyan sediments in the north. A large body of granodiorite along with gneisses is exposed near Dudhi to the south of Mahakoshal Group. These gneisses are considered as equivalents of the Bundelkhand granite and contain numerous enclaves of quartz-mica schist, quartz-sillimanite schist, crystalline limestone, BIF, amphibolite and talc-chlorite schist. The overall composition of Dudhi gneiss is hornblende granodiorite.

*Sleemanabad Formation* is best exposed between Sleemanabad and Vilayat Kalan in the west and around Chitrangi in the east, and consists essentially of basaltic flows associated with ultramafic-mafic plugs. The base of the formation is not prominently exposed, but its top consists of the polymict conglomerate of Parsoi Formation. The sediments of Sleemanabad Formation commence with a quartzite near the base, but are dominated by carbonates, bedded and massive chert, manganiferous chert, BIF and greywacke-phyllite. Quartzite shows cross stratification and carbonates are stromatolitic, containing species of *Colonella*, *Baicalica*, *Kussiella* and *Stratifera*. The sediments underlie metabasalts as evidenced by the way-up criteria in pillow structures. The lithological association of quartzite-carbonate-chert-BIF suggests alluvial to shallow marine and intertidal environment.

Fe-rich tholeiites interfinger with the sediments in the upper part of the formation consisting of greywacke-phyllite. Metabasalts consisting mainly of actinolite, chlorite and sodic plagioclase show amygdular and pillow structures, along with abundant pyroclastics. Locally picritic basalts are also found. Extreme carbonate alteration, tendency for alkalinity and compositional variation suggest submarine alteration. High REE contents and flat HREE patterns indicate low degree of partial melting at shallow levels in the upper mantle. Some serpentinised ultramafic plugs associated with Mahakoshal basic volcanics carry asbestos veins.

*Parsoi Formation* is essentially a greywacke-argillite suite with some carbonaceous phyllite and quartz arenite. A polymict conglomerate containing pebbles of BIF, chert, jasper, quartzite and vein quartz defines the base of the formation and marks an unconformity at Sleemanabad and Lametaghat. The upper part of Parsoi Formation is marked by the first appearance of a persistent BIF horizon. Turbidites with interbeds of BIF marking quiescent conditions indicate a deep shelf-slope environment for Parsoi Formation. In the east, Parsoi and Sleemanabad Formations are juxtaposed along the syn-depositional Amsi-Jiyawan Fault. Gold prospects like those of Gurhar Pahar and Guladih are located within the Parsoi Formation.

*Dudhamaniya Formation* is mainly an argillite suite with thin interbeds of greywacke. Several BIF bands, including manganiferous cherts, are closely interbedded with argillite suggesting quiet conditions of deep shelf.

### *Structure and Metamorphism*

Mahakoshal belt has undergone three phases of deformation with an overall ENE-WSW disposition controlled by the original linearity of the basin that is accentuated by the two main deformational episodes. The first phase of deformation produced upright to inclined folds on steep south-dipping axial planes. These folds are weakly non-cylindrical and gently plunging with pervasive cleavage. The second phase of deformation produced vertical to reclined, E-W striking folds with steep south-dipping axial planes and crenulation cleavage. The third phase of deformation produced broad warps and small-scale folds on N-S striking axial planes.

Mahakoshal belt is characterised by regional greenschist facies metamorphism. Higher metamorphic grades are seen in the southern margin where SNSF is associated with granitic intrusions. These granites are responsible for the low-pressure meatamorphism of the belt, which is reflected by the presence of porphyroblasts of garnet, andalusite, staurolite and cordierite (Fig.4S-4a) in pelites and meta-tuffs, and Mn garnet-grunerite assemblage in BIF. The peak metamorphic P-T conditions inferred from petrogenetic grids is 550°C at 3-3.5 kb, followed by retrogression that is marked by chlorite-biotite assemblages in pelites (Roy et al. 2002a).

### *Intrusions*

Mahakoshal belt is intruded by granites on either side of the belt along the SNNF and SNSF. Important granite bodies are Madanmahal, Barambaba, Jhirgadandi, Tamakhan and Rihand-Renusagar, along with some albite granites. Some of these granites are dated by Rb-Sr isochrons, e.g., Jhirgadandi monzodiorite (1750±100 Ma; 1708±40 Ma and 1813±65 Ma), Tamakhan granite (1856±68 Ma) and Rihand-Renusagar granites (~1730 Ma). Barambaba granite indicates a higher age range of 2000-2400 Ma, and since this age is not consistent with that of similar granites, it may denote the age of basement. The granites away from the shear zone show pre-full crystallization (magmatic) fabrics (Fig.4S-4b), and within the shear zone are deformed into mylonites (Fig.4S-4c). Funnel-shaped syenite intrusions are seen in the northern margin at Bari, Kusumhar and Satohari. Bari syenite gives Rb-Sr age of ~1800 Ma. Syenites are associated with trachytic dykes, lamprophyres (dated around 1600-1800 Ma), carbonatites (?) and barytes veins. Some alkali gabbros and lamprophyres indicate a range of Rb-Sr ages from 1610 to 1760 Ma. Ultramafic-mafic intrusions (e.g. websterite, gabbro) mark the end phase of intrusive activity as evidenced by quartz veins transecting them. Quartz porphyry dykes and numerous quartz veins, some associated with gold mineralisation, are also common. Dolerite dykes cut across all the formations. The available dates suggest an age range of 1700-1800 Ma for Mahakoshal Group, similar to the age of the undeformed sediments of Bijawar Group in the north.

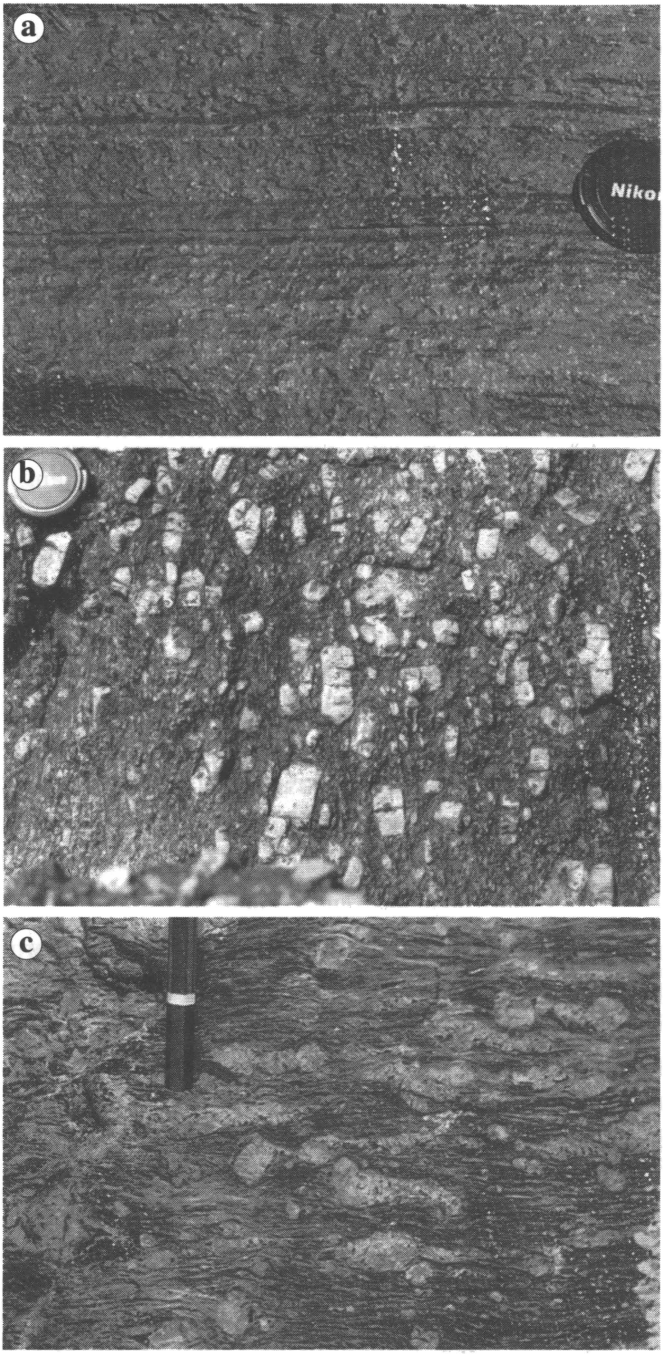


**Fig.4S-4.** (**a**) Development of cordierite porphyroblasts controlled by lamination in metapelite. Gopad River section (from Roy and Devarajan, 2000, p.91). (**b**) Pre-full crystallization fabric in the granite from the southern margin of Mahakoshal belt, Singrauli (Roy and Hanuma Prasad, 2003 with permission from Elsevier). (**c**) Mylonite with porphyroclasts of K-feldspar megacrysts and quartz ribbons, north of Singrauli (from Roy and Devarajan, 2000, p.89).

### *Evolution of Mahakoshal Basin*

Mahakoshal basin was probably initiated as a pericratonic, fault-bounded basin with initial fluvial to shelf sedimentation starting in the south of SNNF. This basin probably evolved contemporaneously with the intra-cratonic Bijawar basin sited on Bundelkhand granite at about 1800 Ma ago. The basin was originally regarded as an intracontinental rift, but later studies identified the calc-alkaline granitoids occurring in its southern margin as arc-related, suggesting that the basin could be a back-arc rift. The shelf sediments overlain by tholeiitic basalts, greywacke turbidites, and deep-water shales interbedded with BIF bands suggest the deepening of the basin towards the south. Geochemically, the basalts plot in the fields of MORB, OIB or continental rift, and therefore are not diagnostic of any specific environment. Ultramafic intrusions are younger and the mafic-ultramafic association does not conform to the known characteristics of ophiolites. The deformation of the belt is characterised by north to northwest-directed sub-horizontal compression. Convergent margin tectonism is indicated by the presence of contractional regime and emplacement in the shear zone of sheet-like calc-alkaline granitoids of the compositional spectrum that is characteristic of mantle-crust interaction. The presence of granulite enclaves and boudins in the gneisses at Makrohar and Rihand Dam support the view of convergent tectonics in the evolution of Mahakoshal fold belt.

## Son-Narmada South Fault (SNSF)

The nearly E-W trending SNSF demarcates the southern margin of Mahakoshal belt and extends for over 700 km, dipping at a steep angle to the south. It was probably formed in Palaeoproterozoic and has since been repeatedly reactivated. Several phases of sheet-like granite belonging to granodiorite-granite-adamellite (GGA) suite intrude the shear zone. The NE-trending magmatic fabrics of granites are superposed by E-W trending tectonic fabrics. The shearing and granite intrusion are coeval with the second phase of deformation in Mahakoshal belt.

## Makrohar Granulite Belt

The granitic rocks to the south of SNSF contain enclaves of amphibolite to granulite facies near Makrohar and Waidhan close to the Rihand Dam, where the gneisses occurring as a tongue are contiguous with the vast terrain of Chhotanagpur Gneiss situated in the east. The enclaves are sillimanite quartzite, corundum-sillimanite-quartz schist, garnet-cordierite-sillimanite-biotite granulite, amphibolite and retrograded mafic granulites, BIF and calc-silicate rocks. The pelitic granulites of Waidhan area are estimated to have experienced a peak metamorphic condition at 800°C and 5 to 6 kb, followed by isothermal decompression at 740°C and 6.5 kb, and final re-equilibration at ~685°C at 6 to 6.5 kb. The clockwise P-T path deduced for these granulites indicates convergent tectonics in their evolution. The age of granulite facies metamorphism is not constrained, but by interpolation with the Rb-Sr age of the gneisses, may be reckoned at 1.7-1.8 Ga.

### Balrampur Fault

Balrampur Fault (also called Shahdol Lineament) passes through Gondwana sediments, Betul belt margin and gneisses, and is marked by shearing, breccia zones, hot spring (Tatapani) and dolerite dykes.

## Betul Supracrustal Belt

Betul belt (Fig.4S-5a) trending ENE-WSW, extends for about 135 km from Betul in the west to Chhindwara in the east over a width of about 15-20 km, and is situated between the Mahakoshal and Sausar supracrustal belts. The belt is overlain by Gondwana sediments and Deccan Trap on all three sides, but for a narrow corridor near Kanhan through which it is connected to the gneissic terrain in the north of Sausar belt. SNSF separates the Mahakoshal belt and the gneisses of CITZ. A major ductile shear zone called the Tan Shear

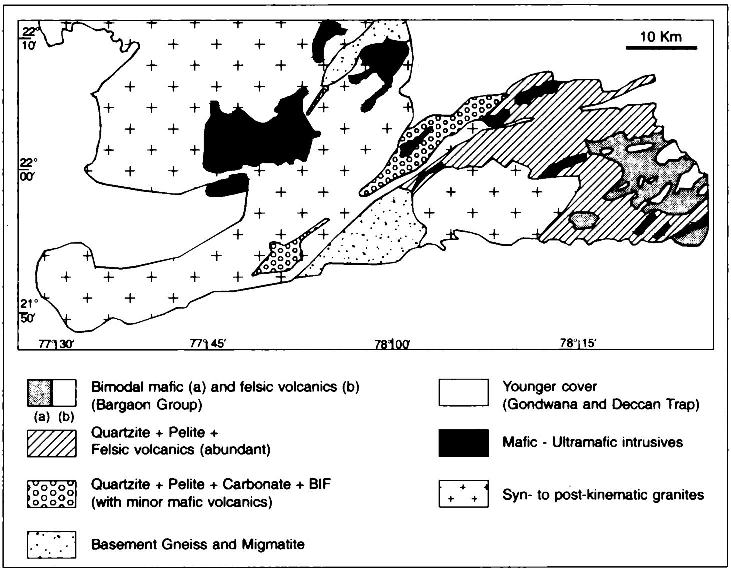

22° 10'
22° 00'
21° 50'
77°30'
77°45'
78°00'
78°15'
10 Km
(a) (b)
Bimodal mafic (a) and felsic volcanics (b) (Bargaon Group)
Quartzite + Pelite + Felsic volcanics (abundant)
Quartzite + Pelite + Carbonate + BIF (with minor mafic volcanics)
Basement Gneiss and Migmatite
Younger cover (Gondwana and Deccan Trap)
Mafic - Ultramafic intrusives
Syn- to post-kinematic granites

**Fig.4S-5a.** Geological map of the Betul belt (after Roy and Hanuma Prasad, 2003, with permission from Elsevier).

Zone (TSZ) occurs between the Betul and Sausar belts. Betul belt is bounded by Balrampur Fault in the north and is dissected by a series of parallel faults, e.g. Machna, Sarni and Sonaghati faults. A major NNE-SSW trending cross fault divides the belt into two halves. Betul belt consists essentially of unclassified gneisses and granites and many supracrustal ensembles whose mutual relationships are unclear. The belt has been recently explored for Pb-Zn mineralisation.

Early work in the Betul belt has been rather sketchy. Geological mapping by the Geological Survey of India between 1990 and 1995 has resulted in a preliminary synthesis of its complex stratigraphy (Srivastava and Chellani, 1996; Chaturvedi, 2001). Geological summaries of the belt have been given by Roy et al. (2000), Roy and Hanuma Prasad (2003), Roy et al. (2004) and Raut and Mahakud (2004).

### *Stratigraphy*

A tentative stratigraphy of Betul supracrustal belt is given in Table 4S-3.

**Table 4S-3.** Lithostratigraphy of Betul Belt

| | |
|---|---|
| Younger Granite (850±15 Ma) | Pink and grey undeformed potassic granite |
| Padhar Mafic Intrusion | Gabbro, norite, pyroxenite and diorite |
| Bhopali Group | Dolomitic limestones, calc-silicate rocks, BIF, calc-phyllites, mica schists, quartzites and minor basic volcanics |
| | Augen gneiss |
| Bargaon Group | Pillowed tholeiitic basalts, magnesian basalts, pyritiferous cherts, acid volcanics and pyroclastics |
| | Magnesian schists (anthophyllite-cummingtonite schists), garnet-staurolite-biotite-gahnite schists, graphitic schists, calc-silicate rocks |
| Amla Gneiss (1550±50 Ma) | Banded gneiss, granitic gneiss and migmatite |
| Golighat Group | Enclaves of quartzite, calc-silicate rock, marble, tremolite-actinolite-chlorite-talc schist (ultramafic) and amphibolite |

Betul supracrustal rocks (Betul Supergroup) were earlier correlated with Sausar Group, and the younger Bhopali Group with Mahakoshal Group, but the lithostratigraphic association is different in different areas of the various groups and therefore the correlation is unclear. For example, Betul belt has mafic-felsic volcanics, Mahakoshal Group has mafic volcanics and Sausar Group has little or no volcanics, and these differences help to broadly distinguish them as separate groups.

*Amla Gneiss and Golighat Group:* The gneisses surrounding the Betul belt are called *Amla Gneiss* having Rb-Sr date of 1550±50 Ma for the gneiss at Morkha. The gneiss forms basement to the Bargaon and Bhopali Groups, as evidenced by local unconformable relations. Numerous enclaves of older metamorphics, variously named as Kosmi, Temri and Sonaghati Formations from different local sections, have been clubbed together under the *Golighat Group.* The older metamorphic enclaves are quartzite, quartz-mica schist, dolomitic marble, calc-silicate rock, tremolite-actinolite-talc-chlorite schist (ultramafic) and amphibolite. Granulite grade BIF is also reported. *Golighat Group* is best exposed in the western and northern parts of the belt. There is, however, an alternate opinion that these enclaves have similarities with the metamorphosed and migmatized rocks of the younger Bhopali Group, in which case they may form a single suite. This is a common problem of most metamorphic terrains that needs to be resolved through more detailed studies.

*Bargaon Group* consists essentially of tholeiitic metabasalts, magnesian basalts, felsic volcanics and pyritiferous cherts. It is best exposed near Bargaon, Tarora and Kherli Bazar in the eastern part of the Betul belt, where it is in tectonic contact with Amla Gneiss. This lithological assemblage has sometimes been loosely called a greenstone association. The metabasalts are pillowed and amygdular, consisting mainly of hornblende and andesine, and are compositionally low-K tholeiites. High magnesian lavas and talc-tremolite schists (ultramafic) are close associates. The felsic volcanics are flow-banded rhyolites rich in Ba (190 ppm to 0.33%) that is closely associated with abundant pyroclastics represented by finely laminated, crystal-, vitric- and lapilli tuffs. The tuffs are associated with unusual sediments (anthophyllite±gedrite-cummingtonite schist) rich in magnesia (20-25%) but poor in Cr, Ni, $CO_2$ and $H_2O$. They contain CaO (10-14%), FeO (5-8%), silica (51-56%) and low Al (2.5 – 4%) and may be a mafic tuff. The other sediments are biotite-garnet-staurolite schists with gahnite (zinc spinel) that host sulphide (Zn-Cu-Pb) mineralisation of stratiform, submarine exhalative type. Younger granites (850±15 Ma) intruding Bargaon Group have been converted to augen gneisses and granitic mylonites along shear zones.

*Bhopali Group* represents younger sediments exposed in the western and central parts of the belt. The sediments are mainly phyllites intercalated with graded-bedded and cross-bedded quartzites, dolomitic limestones, calc-phyllites and BIF. Near Ghoda Dongri, the sediments are intercalated with greenschist facies metabasalts. Bhopali Group has unconformable contact with the basement of Amla Gneiss locally, but elsewhere the contact is tectonic.

*Padhar Mafic Intrusion* represents a large suite of mafic-ultramafic rocks trending ENE-WSW and covers over 160 km$^2$ in the northern part of the belt near Gajpur and Padhar, and is locally called as Padhar Formation. It is emplaced in the strongly deformed and metamorphosed sequence of Bargaon and Bhopali Groups, but is itself undeformed, except in shear zones where it becomes schistose. Granulite grade BIF, calc-silicate rock and amphibolite occur as enclaves within the intrusion. The intrusion consists of a northern mafic zone, a central ultramafic zone and a southern mafic zone. The mafic-ultramafic suite consists of discrete sheets and plutons of olivine websterite, pyroxenite, hornblendite, hornblende gabbro, norite and diorite. Cumulus texture is common, as in any layered intrusion. Clinopyroxene is diopside and augite, orthopyroxene is clino-enstatite, and amphibole is tschermakite to magnesio-hornblende. Primary phlogopite is found in pyroxenite. The mafic-ultramafic rocks are enriched in LREE (10 to 2000 times over chondrite) with gently sloping HREE and $(La/Yb)_N$ ratios of 4 to 8, suggesting derivation from an enriched mantle source, and subsequently contaminated by continental crust during emplacement. The layered intrusion is produced by crystal settling from the parent magma of tholeiitic composition.

*Younger Granite:* Syn- to post-tectonic, porphyritic to homophanous granites are emplaced along ENE-WSW trending ductile shear zones. Steep northerly dipping foliation and low to moderate plunging lineations suggest oblique-slip movement. A younger granite at Navegaon yields Rb-Sr age of 850±15 Ma.

*Structure:* The rocks of Betul belt have undergone three phases of progressive deformation. The first phase produced isoclinal to reclined folds on ENE striking axial planes, whereas the second phase coaxially refolded them (Fig.4S-5b). The third phase produced cross folds in the belt.

A number of ENE striking and steep northerly-dipping ductile shear zones has developed simultaneously with early folding. The shear zones host widespread granitic magmatism. Metamorphism is of middle to upper amphibolite facies in Golighat enclaves, middle amphibolite facies in Bargaon Group and greenschist facies in Bhopali Group. Local granulite grade outcrops of BIF are also noticed.

*Tectonic Setting:* The presence of low-K tholeiites, bimodal volcanics and younger calc-alkaline granitoids suggests a continental margin arc setting for the Betul belt. The presence of ~1500 Ma syntectonic granite, and ~850 Ma late- to post-tectonic granite suggests that Betul belt may be penecontemporaneous with Mahakoshal belt, with Betul belt marking the

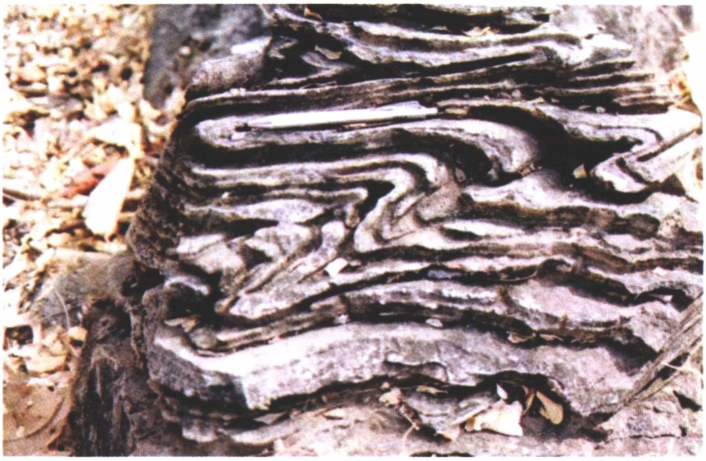


**Fig.4S-5b.** Refolded fold (hook-shaped) in the calc-silicate rock of Betul belt near Arjangundi (Roy and Hanuma Prasad, 2003, with permission from Elsevier).

magmatic arc containing intra-arc sedimentary belts, and Mahakoshal belt representing a back-arc rift at the old continental margin.

### Tan Shear Zone

The NE to ENE trending TSZ extends for over 900 km from Seoni in the west to Ambikapur in the east in the central part of CITZ. It is traced into Gavilgarh fault occurring further west. The thickness of shear zone varies from 1 to 7 km with an average of 2 km. Concordant sheets and plutons of granite intrude the shear zone and have developed mylonitic foliation, as in SNSF. The granites contain enclaves of calc-silicate rock. The granitic rocks belong to the granodiorite-alkali granite suite, which are peraluminous and calc-alkaline, like the collision-related granitoids. An Rb-Sr age of 1147±16 Ma with a high $I_{Sr}$ ratio suggests crustal derivation. Charnockite-mangerite suite is reported along the TSZ near Mandla and these may be coeval with granitic magmatism. These granulites may form the eastern extensions of granulite enclaves (BIF etc) near Betul belt.

### Ramakona-Katangi Granulite Belt (RKG Belt)

The RKG belt is 250 km long, consisting of granulite lenses, boudins and enclaves occurring within migmatitic gneisses and granites. The granulites are represented by retrograded pyroxene granulites and garnet-cordierite granulites tectonically interleaved with metasediments. The granulites record peak metamorphism of 850°C/8 kb, followed by decompression at 800°C/4 kb and a cooling phase at 650°C/4 kb, marking a clockwise P-T evolutionary path signifying collision. There is a difference of opinion as to whether this association represents a single cycle Sausar orogeny or a multi-cycle pre-Sausar and Sausar orogenies. In the multiple cycle model, this high-pressure granulite belt may mark an oceanic subduction zone, followed by collision during Sausar orogeny.

Syntectonic granites emplaced in the granulite belt exhibit steep northerly dipping foliation and down dip mineral lineation. DSS profile also confirms the north-dipping fault that is consistent with Bundelkhand craton overriding the Bastar craton along this granulitic suture belt.

### Sausar Supracrustal Belt

Sausar belt (Fig.4S-6) extends for a length of over 215 km from Ramakona to Baihar with an average width of 35 km and covers an area of about 7000 km$^2$. It is an arcuate fold belt trending ENE-WSW with convexity to the south. This belt has been found recently to extend further east as Bilaspur-Raigarh belt up to Ratanpur. Sausar belt is surrounded by Tirodi gneiss, and is separated from the Betul belt in the north by the Tan Shear zone and from the Bastar craton in the south by the CISZ (Central Indian Shear Zone). In close association with the shear zones are two major granulite belts bounding the Sausar belt, namely the Ramakona-Katangi granulite belt in the north and the Bhandara-Balaghat granulite belt in the south. Lithologically, the belt is dominated by quartzite-carbonate-pelite (QCP) suite, with little or no volcanics. The richest manganese deposits of India occur in the mica schists of Mansar Formation and the carbonate rocks of Lohangi Formation.

*Stratigraphy:* The stratigraphy and structure of the Sausar belt have been a matter of debate for a long time. Chattopadhyay et al. (2001), Mohanty (2003) and Chattopadhyay and Bandyopadhyay (2004) provide recent geological summaries of Sausar fold belt. The most comprehensive and widely followed stratigraphic scheme is that of Narayanaswami et al. (1963), which is given in Table 4S-4.

There are many stratigraphic problems of Sausar belt that are due to widespread lithofacies variations as a result of which the correlation of different stratigraphic sections becomes a matter of opinion. Further, Sausar belt is typified by complex deformation involving recumbent folding, thrusting and nappe formation, which complicate the order of superposition. The much-debated Deolapar nappe reported by West (1936) as well as the Mogra and Sapghota nappes described by others later, have raised the question of 'normal' and 'inverted' sequence, with the result even the presence of nappes have been called into question. There is, however, a general consensus

**Table 4S-4.** Lithostratigraphy of Sausar Group (after Narayanaswami et al. 1963)

| | |
|---|---|
| Bichua Formation | Dolomite marble and calc-silicate rocks |
| Junewani Formation | Muscovite-biotite schist and quartz-biotite schist |
| Charbaoli Formation | Quartzite and quartz-muscovite schist |
| Mansar Formation | Mica schist, graphitic phyllite and quartzite<br>Manganese ores and 'gondite'* |
| Lohangi Formation | Calcite and dolomitic marble, manganese ore, calc-silicate rock, epidote quartzite and quartz-biotite schist |
| Sitasaongi Formation | Quartz-mica schist, quartzite and basal conglomerate |
| - - - - - - - - - - - - - | - - - - - - - - - - - - - - -Unconformity - - - - - - - - - - - - - - |
| Tirodi gneiss | Biotite gneiss and migmatite with enclaves of amphibolite, calc-silicate rock, mica schist etc. |
| Older Metamorphic Group | Charnockite, orthogneiss, garnet-biotite paragneiss, Mg-Al pelite, calc-granulite and amphibolite |

*'Gondite' is a local name for pink to dark grey coloured, manganiferous metasediment composed of braunite, spessartite, rhodonite, rhodochrosite and a variety of manganese amphiboles. Gondite contains pockets of manganese ore consisting of many primary oxides like jacobsite, hausmannite, hollandite, bixbyite etc. and supergene oxides like pyrolusite, psilomelane, cryptomelane etc.

that regional stratigraphic inversion by recumbent folding has not occurred, with the result the stratigraphic sequence of Narayanaswami et al. (1963) continues to be more or less valid.

There have been many attempts to modify the stratigraphic scheme of Narayanaswami et al. (1963), but these are limited only to local areas, and are not applicable on a regional scale. Several horizons of marbles, pelites and manganese formations having differences in lithological characters have been mapped in the Sausar fold belt, but it is uncertain whether they represent stratigraphic order, structural repetition or facies change. Further, if the sillimanite-nodule ("sillimanite tabloid") bearing gneisses that were earlier mapped as Mansar or Junewani Formation, were to be viewed now as part of Tirodi gneiss, many stratigraphic problems will arise. Therefore, unless a holistic picture emerges, the classification of Narayanaswami et al. (1963) will hold good.

Another major stratigraphic issue is the basement-cover problem. Tirodi gneiss was considered in earlier literature either as basement or as intrusive into the Sausar supracrustals. Recent studies have shown the Tirodi gneiss to be basement, because the gritty and pebbly quartzite of the basal Sitasaongi Formation overlies the Tirodi gneiss marking the unconformity at the Chikla-Sitasaongi area. A polymict, granite-clast conglomerate having micaceous matrix occurs at the base of Sausar Group at the Gangulpara Ghat section to

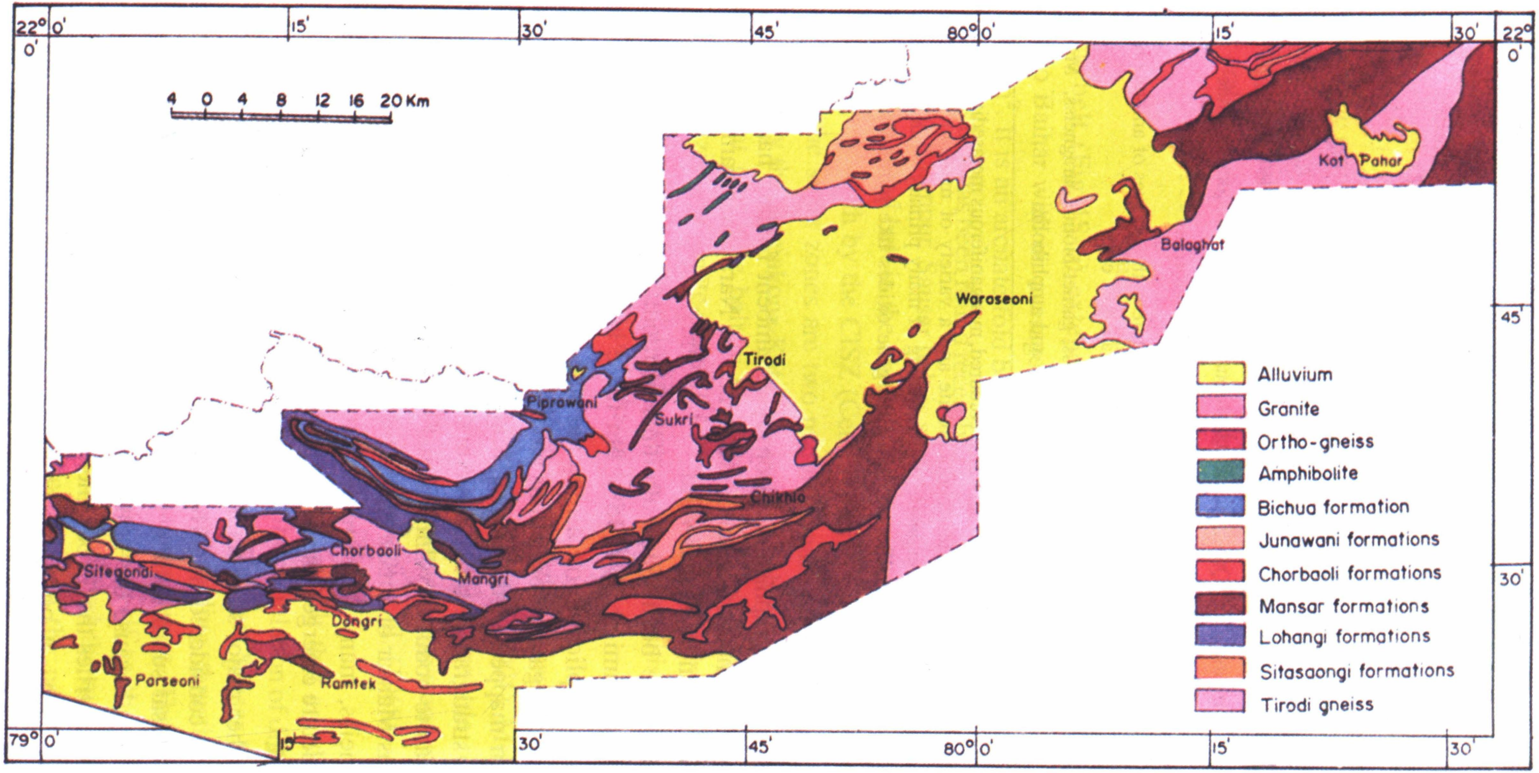

22° 0'
0'
15'
30'
45'
80° 0'
15'
30'
22° 0'
45'
30'
79° 0'
4 0 4 8 12 16 20 Km
Kot Pahar
Balaghat
Waraseoni
Tirodi
Piprawani
Sukri
Chikhla
Chorbaoli
Sitagondi
Mangri
Dongri
Ramtek
Parseoni
Alluvium
Granite
Ortho-gneiss
Amphibolite
Bichua formation
Junawani formations
Chorbaoli formations
Mansar formations
Lohangi formations
Sitasaongi formations
Tirodi gneiss

**Fig.4S-6.** Geological map of the Sausar belt by Narayanaswamy et al. (1963). Reproduced from Bandyopadhyay et al. (1995).

the northeast of Balaghat town. Some authors, however, interpret the Gangulpara conglomerate as glacial in origin. Elsewhere, a palaeosol horizon is also reported at the basement-cover contact. The glacial origin of conglomerate and presence of palaeosol need further investigation for confirmation. Some investigators suggest that the Gangulpara polymict conglomerate may mark the base of a younger sequence (called by them as *Bharweli Group*) and not of the Sausar Group, but this view has not found favour with most other workers. The sum total evidence is, however, in favour of an unconformity at the base of the Sausar Group over the Tirodi gneiss basement.

Those who view Tirodi gneiss as intensely folded together with Sausar schists, point out features of 'granitisation' of the Sausar sediments or invasion by anatectic melts of Tirodi gneiss into the Sausar Group. Others argue that the Sausar Group does not cross the K-felspar-sillimanite isograd to cause partial melting of the metapelites and therefore Sausar metamorphism does not exceed amphibolite facies P-T conditions. They opine that the 'sillimanite tabloids' (quartz-fibrolite nodules) in Tirodi gneiss have formed due to the breakdown of felspar, and that the nodules do not form part of pelitic schists of Sausar Group, as believed earlier. This is a debatable point because quartz-fibrolite nodules are abundantly developed in the garnet-biotite-muscovite schists of Sausar Group and not in other horizons, not even exclusively within the Tirodi gneiss. The controversy can be resolved by viewing Tirodi gneiss as basement (as clearly seen in some areas) that has been remobilised or partially melted during the Sausar orogeny to show such 'intrusive' phenomena as granitisation or quartzo-felspathic veining of the Sausar sediments. In such a case, the Sausar metapelites need not necessarily have partially melted concurrently.

Recently, it was found that the Sausar Group extends to the east as Bilaspur-Raigarh belt on the northern fringes of Chhattisgarh Purana basin, and continues further east as inliers within the Mahanadi Gondwana basin. The Bilaspur-Raigarh belt trending nearly E-W is divisible into a northern part containing calc-silicate rocks, quartzites and mica schists that are correlatable with the Sausar Group, and a southern part consisting of greywacke-phyllites, felsic volcanics, BIF and cherts that may be correlatable with the Chilpi Group. The northern and southern parts of this belt are separated by the major CISZ passing through the area.

*Structure:* Deformation of Sausar belt commenced with low angle imbricate thrusting and tectonic interleaving of the basement and cover, as seen in Deolpar nappe, Sapghota thrust and Sonawani thrust. Thrusting is accompanied by tight isoclinal, recumbent, reclined to sheath folds, on a broad E-W striking axial plane, associated with penetrative schistosity and mylonitic foliation. Recumbent folding causing regional stratigraphic inversion has not so far been clearly documented.

The early folds ($F_1$) were refolded by mapscale upright to steeply inclined non-cylindrical $F_2$ folds with a gentle plunge to the E or SE. Tirodi gneiss has participated in the $F_2$ deformation. Superposition of $F_1$ and $F_2$ folds has given rise to hook-shaped interference patterns. The $F_3$ folds are seen mainly on outcrop scale without significant penetrative fabric, and are generally upright folds with a low easterly plunge. The final $F_4$ folds are open warps on N-S axial planes with low east plunging axes. Several cross faults and shear zones have developed late in the deformation sequence, and some are brittle faults related to the evolution of Gondwana basins and Deccan Trap.

*Metamorphism:* Earlier workers have recorded Barrovian regional metamorphism (kyanite-sillimanite type) of greenschist facies in the south to amphibolite facies in the north in the Sausar belt. Recent thermobarometric studies record peak metamorphic conditions of 675°C at 7kb, followed by the decompressional phase of about 550°C at 4kb. The clockwise P-T loop and the presence of widespread thrusting indicate collisional orogeny.

### Balaghat-Bhandara Granulite (BBG) Belt and Central Indian Shear Zone (CISZ)

Central Indian Shear Zone truncates the dominant N-S structural trends of Kotri-Dongargarh, Sakoli and Sonakhan belts of Bastar craton (vide Chapter 3), along a major ENE-WSW shear zone running for 200 km in length with a width of a few kilometers. The shear zone is marked by intense mylonitisation involving a variety of lithologies such as granitic gneisses, and other supracrustal lithologies. Narrow lenses of basic granulites, Mg-Al pelites, Al-rich (kyanite) pelites, BIF, and garnet-sillimanite quartzites associated with boudin-type charnockites and enderbites are seen all along the shear zone. The basic granulites are interpreted as evolved tholeiites, and the supracrustals, especially the high-pressure metamorphic Mg-Al pelites, are regarded as pre-Sausar in age. Shear zone indicators suggest thrusting of the granulite belt over the Amgaon gneiss of the Bastar craton. Two phases of pre-Sausar granulite facies assemblages are recorded from this belt. The first phase records 900°C/7 kb, whereas the second phase records 700°C/8kb and marks a post-peak IBC path. The granulite metamorphism is believed to be overprinted by the amphibolite facies metamorphism of the Sausar fold belt.

*Age Relations*: Charnockite from BBG belt has yielded Sm-Nd age of 2672±54 Ma which may indicate the Archaean basement age. Sm-Nd and

Rb-Sr ages of charnockites and pyroxene granulites at ~1400 Ma and Ar-Ar age of hornblende from the belt of 1300 Ma, together with the Rb-Sr age of Tirodi gneiss (1525±70 Ma), suggest a major metamorphic event at 1400-1500 Ma (*see* Roy et al. 2004a). Ar-Ar ages of manganese minerals at 980 Ma, Rb-Sr ages of charnockites of BBG belt at 973±63 and 800±16 Ma, along with 860 Ma of Rb-Sr mineral age of Tirodi gneiss, probably indicate the age of Sausar metamorphism, which is also corroborated by the Rb-Sr age of 1147±16 Ma of granites from Tan shear zone situated to the north of the Sausar belt.

## Tectonic Evolution of CITZ

There are two plate tectonic models that explain the evolution of CITZ. Yedekar et al. (1990) first proposed (Fig.4S-7a) that the Bundelkhand craton subducted below the Bastar craton along the Central Indian Suture (CIS). Mahakoshal belt was interpreted as intracratonic rift and the Sausar belt as

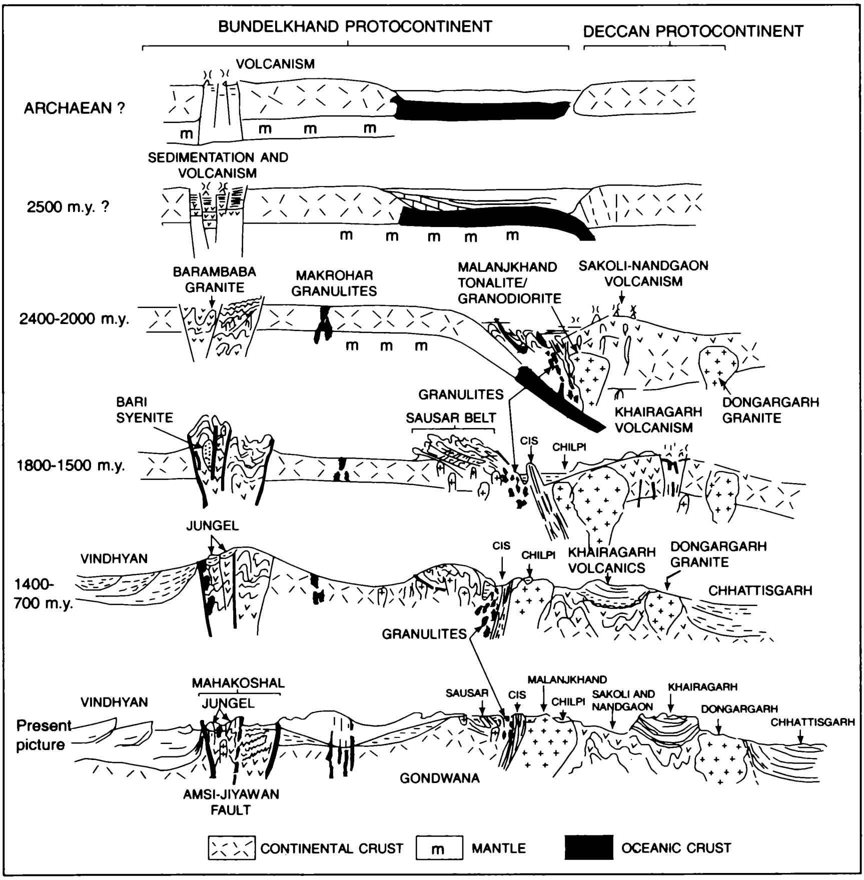

BUNDELKHAND PROTOCONTINENT
DECCAN PROTOCONTINENT
VOLCANISM
ARCHAEAN ?
m
SEDIMENTATION AND VOLCANISM
2500 m.y. ?
BARAMBABA GRANITE
MAKROHAR GRANULITES
MALANJKHAND TONALITE/ GRANODIORITE
SAKOLI-NANDGAON VOLCANISM
2400-2000 m.y.
BARI SYENITE
GRANULITES
SAUSAR BELT
KHAIRAGARH VOLCANISM
DONGARGARH GRANITE
CIS
CHILPI
1800-1500 m.y.
JUNGEL
VINDHYAN
1400-700 m.y.
CIS
CHILPI
KHAIRAGARH VOLCANICS
DONGARGARH GRANITE
CHHATTISGARH
GRANULITES
MAHAKOSHAL
VINDHYAN
JUNGEL
Present picture
AMSI-JIYAWAN FAULT
GONDWANA
SAUSAR
CIS
MALANJKHAND
CHILPI
SAKOLI AND NANDGAON
KHAIRAGARH
DONGARGARH
CHHATTISGARH
CONTINENTAL CRUST
MANTLE
OCEANIC CRUST

**Fig.4S-7a.** Model of evolution of CITZ (after Yedekar et al. 1990).

continental margin sediments of the Bundelkhand craton. They suggested that subduction was initiated around 2700 Ma, suturing at 2100-1800 Ma and the culmination of orogeny with granulite exhumation at 1300-1400 Ma. The Sakoli and Dongargarh volcanics were considered as arc-related volcanics associated with subduction. The basic granulites of CIS were interpreted as MORB basalts, which have been obducted during the convergence. The tectonic environments of basic rocks, however, are interpreted using inconclusive geochemical discrimination diagrams.

S.K. Acharyya (Fig.4S-7b) and A. Roy and co-workers (Fig.4S-7c) have proposed an alternative plate tectonic model based largely on the thermobarometric studies of the granulites in the CITZ by S.K. Bhowmik and

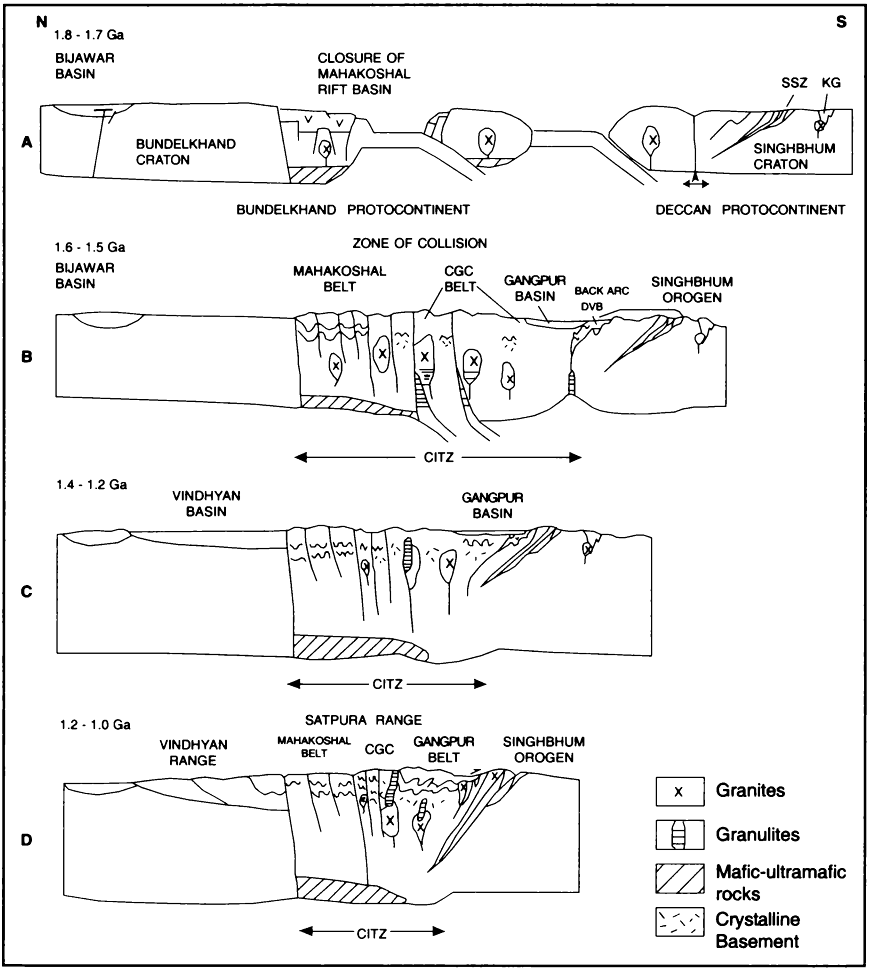

N
S
1.8 - 1.7 Ga
BIJAWAR BASIN
CLOSURE OF MAHAKOSHAL RIFT BASIN
SSZ
KG
A
BUNDELKHAND CRATON
SINGHBHUM CRATON
BUNDELKHAND PROTOCONTINENT
DECCAN PROTOCONTINENT
1.6 - 1.5 Ga
BIJAWAR BASIN
ZONE OF COLLISION
MAHAKOSHAL BELT
CGC BELT
GANGPUR BASIN
BACK ARC DVB
SINGHBHUM OROGEN
B
CITZ
1.4 - 1.2 Ga
VINDHYAN BASIN
GANGPUR BASIN
C
CITZ
1.2 - 1.0 Ga
SATPURA RANGE
VINDHYAN RANGE
MAHAKOSHAL BELT
CGC
GANGPUR BELT
SINGHBHUM OROGEN
D
CITZ
X Granites
Granulites
Mafic-ultramafic rocks
Crystalline Basement

**Fig.4S-7b.** Schematic tectonic model of the CITZ (after Acharyya, 2003). KG - Koira Group (Younger Iron Ore Group). SSZ - Singhbhum Shear Zone; CGC - Chhotanagpur Gneiss; DVB - Deccan volcanic basin.

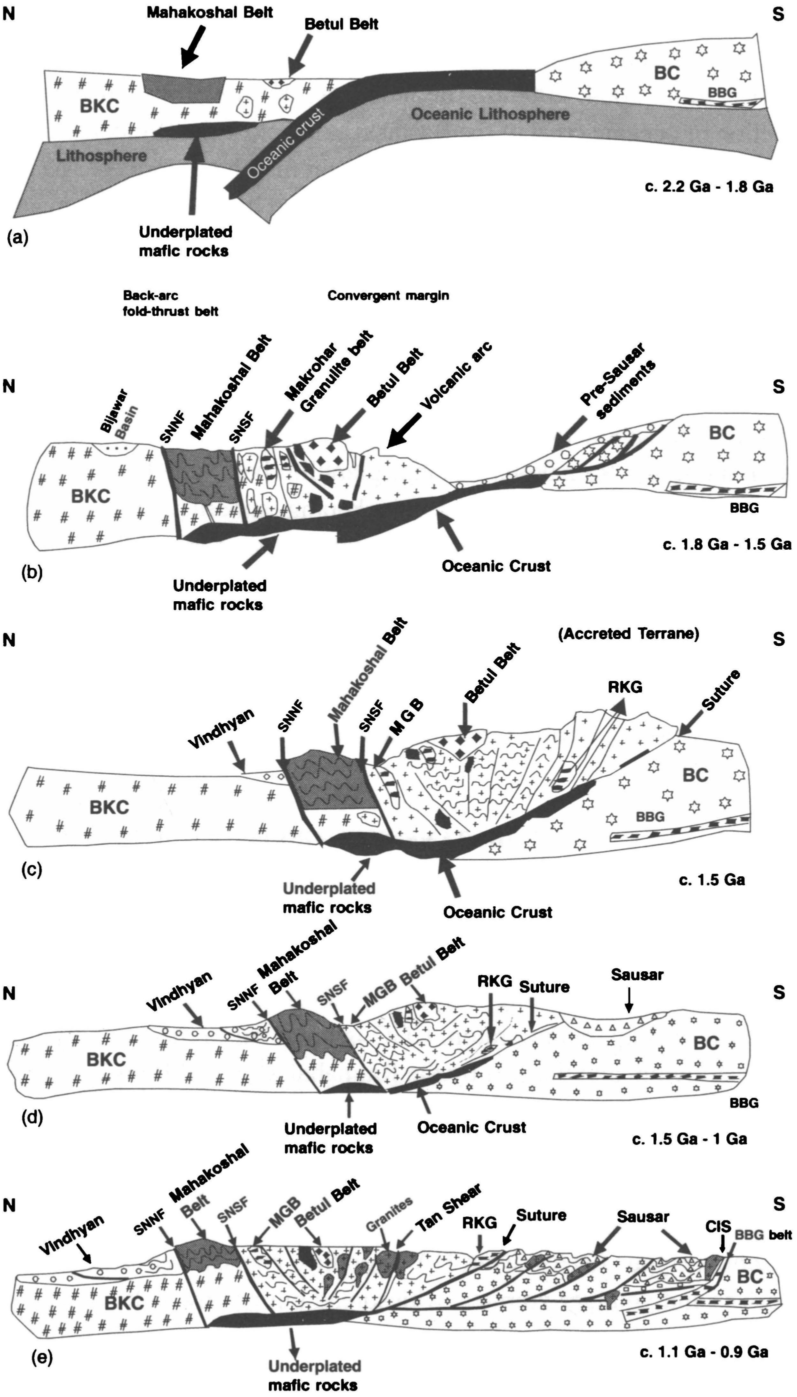

(a)
N
S
Mahakoshal Belt
Betul Belt
BKC
BC
BBG
Oceanic crust
Oceanic Lithosphere
Lithosphere
Underplated mafic rocks
c. 2.2 Ga - 1.8 Ga
(b)
Back-arc fold-thrust belt
Convergent margin
Bijawar Basin
SNNF
Mahakoshal Belt
SNSF
Makrohar Granulite belt
Betul Belt
Volcanic arc
Pre-Sausar sediments
BKC
BC
BBG
Underplated mafic rocks
Oceanic Crust
c. 1.8 Ga - 1.5 Ga
(c)
(Accreted Terrane)
Vindhyan
SNNF
Mahakoshal Belt
SNSF
M G B
Betul Belt
RKG
Suture
BKC
BC
BBG
Underplated mafic rocks
Oceanic Crust
c. 1.5 Ga
(d)
Vindhyan
SNNF
Mahakoshal Belt
SNSF
MGB
Betul Belt
RKG
Suture
Sausar
BKC
BC
BBG
Underplated mafic rocks
Oceanic Crust
c. 1.5 Ga - 1 Ga
(e)
Vindhyan
SNNF
Mahakoshal Belt
SNSF
MGB
Betul Belt
Granites
Tan Shear
RKG
Suture
Sausar
CIS
BBG belt
BKC
BC
Underplated mafic rocks
c. 1.1 Ga - 0.9 Ga

**Fig.4S-7c.** Cartoon showing the tectonic evolution of CITZ (after Roy and Hanuma Prasad, 2003, p.126, with permission from Elsevier). SNNF - Son-Narmada North Fault. SNSF - Son-Narmada South Fault, MGB - Makrohar granulite belt, RKG - Ramakona-Katangi granulite belt. CIS - Central Indian Suture. BKC - Bundelkhand craton, BC - Bastar craton, BBG - Balaghat-Bhandara granulite belt.

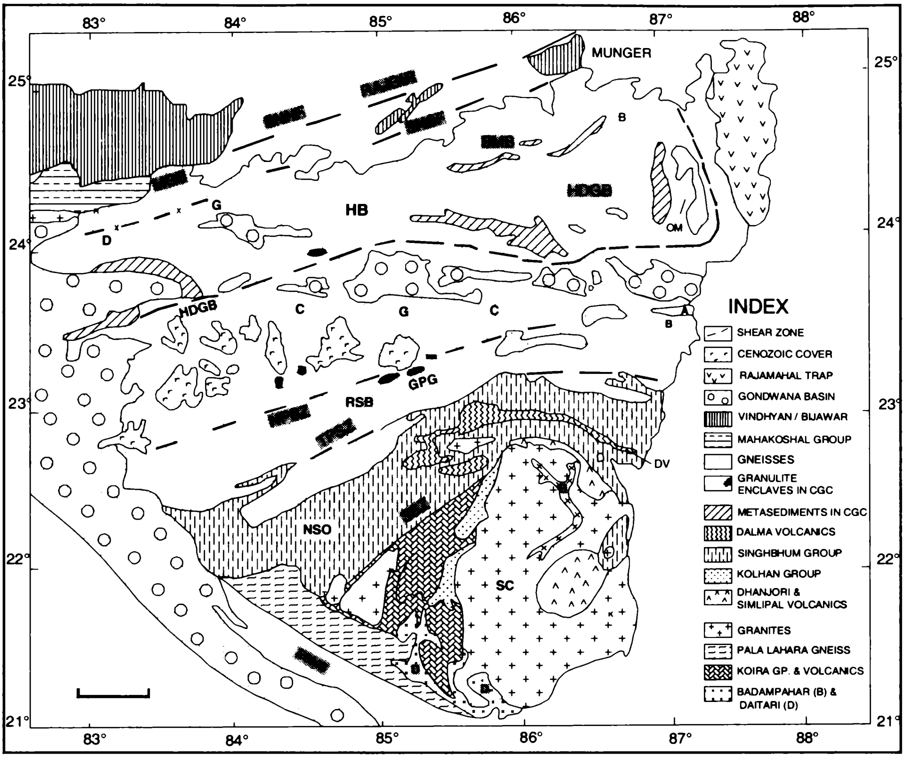
others, besides other new data generated in recent years (Roy and Hanuma Prasad, 2003; Acharyya, 2003a; Bhowmik et al. 2000; Bhowmik and Dasgupta, 2004; Roy et al. 2004, 2004a). The new tectonic model visualises northward subduction of oceanic crust of the Bastar craton below the Bundelkhand craton. According to these authors, Mahakoshal basin may have formed as a back arc rift basin at 2200 Ma, which was closely followed by calc-alkaline magmatism and low pressure metamorphism at 1800 Ma. Calc-alkaline magmatism continued up to 1500 Ma during which period the Betul belt formed as an intra-arc rift filled with bimodal volcanics.

Betul basin closed at 1500 Ma as evidenced by syntectonic granitic rocks, which was accompanied by copious ultramafic-mafic magmatism (Padhar Mafic Intrusion). The subduction culminated at 1500 Ma with continent-continent collision along the Ramakona-Katangi granulite belt, which stitched both the cratons. The collision caused crustal thickening, subcrustal melting and rapid exhumation of granulites. The amalgamated cratons formed the basement for Sausar Group of shelf sediments. The Sausar belt closed at 1100 Ma due to continued thrusting and produced younger granites. The CIS, along with the Balaghat-Bhandara granulite belt, may have formed during or before Sausar deformation. This model envisages pre-Grenvillean collision at 1500 Ma and extensive reworking during Grenvillean orogeny at 1000-1100 Ma.

## CHHOTANAGPUR GNEISS

Chhotanagpur Gneiss (or Chhotanagpur Gneissic Complex, CGC) (Fig.4S-8) covers a vast area of about 500 km long and 200 km wide in eastern India. CGC is bounded to the south by Tamar-Poropahar (or South Purulia) shear zone (TPSZ) separating it from the North Singhbhum orogen occurring to the north of Singhbhum craton. CGC is bounded to the north by the Indo-Gangetic alluvium and the east by the Rajmahal Trap and Bengal basin. In the west it is separated from the CITZ by the Mahanadi Gondwana graben. CGC together with the CITZ, the eastern Aravalli craton (Mewar craton) and the Shillong (Meghalaya) Plateau of North East India, form part of the composite Satpura mobile belt.

Chhotanagpur Gneiss is an E-W trending gneissic terrain with a variety of gneisses and younger granites, widespread but narrow belts of supracrustal enclaves, discontinuous boudin-type granulite belts and major parallel shear zones. The geological setting is therefore the easterly extension of the CITZ beyond the Mahanadi Gondwana graben. Reviews of this terrain are found in Banerjee (1991), Ghose (1992), Mazumder (1988, 1996), Singh (1998), Ghose and Mukherjee (2000), Acharyya (2001, 2003) and Mahadevan (2002). The earlier classifications treated it as a single composite terrain like a craton and


83°
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MUNGER
B
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HDGB
C
G
C
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SHEAR ZONE
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VINDHYAN / BIJAWAR
MAHAKOSHAL GROUP
GNEISSES
GRANULITE ENCLAVES IN CGC
METASEDIMENTS IN CGC
DALMA VOLCANICS
SINGHBHUM GROUP
KOLHAN GROUP
DHANJORI & SIMLIPAL VOLCANICS
GRANITES
PALA LAHARA GNEISS
KOIRA GP. & VOLCANICS
BADAMPAHAR (B) & DAITARI (D)

**Fig.4S-8.** Geological map of the Chhotanagpur Gneiss (CGC) and Singhbhum craton (SC) (after Acharyya, 2003). NSO - North Singhbhum Orogen. EGMB - Eastern Ghats Mobile Belt.

*Tectonic Divisions as in Table 4S-5:* TPSZ - Tamar-Poropahar shear zone, GPG - Gumla-Purulia granulite belt, RSB - Ranchi supracrustal belt, NPSZ - North Purulia shear zone, HDGB - Hazaribagh-Dumka granulite belt, HB - Hesatu-Belbathan belt. BMB - Bihar mica belt, MGB - Makrohar granulite belt, SNSF - Son Narmada South Fault, SNNF - Son Narmada North Fault. SSZ - Singhbhum shear zone, D - Daltonganj, G- Garwa, H - Hesatu, B - Belbathan.

provided a unified stratigraphy. The realization that CITZ is divided into several parallel E-W trending lithotectonic units separated by crustal scale shear zones and boudin-type granulite belts, and that similar geological setting continues into the CGC beneath the younger cover sediments, requires that the stratigraphic scheme will have to be formulated differently in terms of parallel E-W trending belts described by Acharyya (2001) and Mahadevan (2002) and integrated with North Singhbhum Orogen (NSO). The large gaps in continuity between CGC and CITZ due to the extensive younger cover cause formidable problems of regional Precambrian correlation. Further, the numerous sub-parallel faults, shear zones with granulite lenses and boudins along the composite Satpura mobile belt make the one-to-one correspondence difficult, if not impossible. Therefore only a tentative correlation between the Precambrian of CGC, NSO and CITZ is given in Table 4S-5.

**Table 4S-5.** Comparison of units in Satpura mobile belt between CGC, NSO and CITZ

| CGC / NSO | CITZ |
|---|---|
| SNNF | SNNF |
| Mahakoshal | Mahakoshal |
| SNSF | SNSF |
| Makrohar granulite belt | Makrohar granulite belt |
| Bihar mica belt | Betul belt |
| Hesathu-Belbathan belt | |
| North Purulia shear zone | Tan shear zone |
| Hazaribagh-Dumka granulite belt | Ramakona-Katangi granulite belt |
| Kunjar, Gangpur, Ranchi Groups | Sausar Group |
| Gumla-Purulia granulite belt | Balaghat-Bhandara granulite belt |
| Tamar-Poropahar shear zone | CISZ |
| Singhbhum Group | Sakoli (?) and Chilpi Groups |
| Singhbhum craton | Bastar craton |

The description of the various lithotectonic units follows:

### Tamar-Poropahar Shear Zone (TPSZ)

The TPSZ is a convenient reference line to separate CGC from the Singhbhum orogen. This shear zone occurs in strike continuity with the CISZ across the Gondwana graben. There was a view that CISZ links up with the Singhbhum shear zone, but the latter shear zone is limited to North Singhbhum orogen wrapping around Singhbhum granitic basement, and does not extend into CISZ. The rocks in TPSZ are extensively deformed to produce mylonites, cataclasites and phyllonites all along its length. Supracrustal enclaves of phyllites and metabasic schists of Singhbhum Group also occur to the north of shear zone near Manbazar probably as tectonic slices. Basement-cover relations between the CGC and Singhbhum Group are erased by pervasive deformation and metamorphism.

### Gumla-Purulia Granulite Belt

This belt, corresponding to the Balaghat-Bhandara granulite belt of CITZ, is located to the south of the Damodar valley Gondwana basin, and consists of numerous discontinuous granulite enclaves and boudins within gneisses, as seen at Murguma, Ranchi, Purulia and Raghunathpur. The granulites are essentially charnockites and enderbites, basic granulites, prominent bands of garnet-sillimanite gneisses, calc-granulites and hypersthene bearing BIF. These are closely associated with Bankura anorthosites and gabbros, and nepheline syenites of Kushunda and Santuri. Sillimanite-hypersthene bearing metapelites indicate high metamorphic temperatures and pressures (UHT metamorphism) of >1000°C/9-10kb. Thermobarometric studies indicate an ITD path. Rb-Sr whole-rock isochron ages of 1070 Ma for charnockite and ~1180 Ma for migmatitic gneisses suggest that they may be coeval with Sausar deformational episode.

### Ranchi Supracrustal Belt

Trails of supracrustal enclaves of variable shapes and sizes are seen within the gneissic country from Ambikapur to Manbazar and correlate with Sausar belt. The enclaves range in composition from pelites, psammites to calc-silicate rocks and marbles, and show Barrovian metamorphism of amphibolite to granulite facies. The pelitic schists are mainly biotite-muscovite-garnet schists converting to garnet-andalusite-kyanite-staurolite schists and garnet-sillimanite gneisses. The calc-silicate rocks contain tremolite in lower grades and diopside in higher grades. Three phases of deformation with prominent folds having subhorizontal E-W plunge are recorded from Ranchi area.

### North Purulia Shear Zone

The Tan shear zone of CITZ extends to the east under the Gondwana graben into CGC as North Purulia Shear Zone, but has not been studied in detail.

### Hazaribagh-Dumka Granulite Belt

This granulite belt, corresponding to the Ramakona-Katangi granulite belt, occurs to the north of Damodar valley Gondwana basin. In the vicinity of Daltonganj, charnockites are interbanded with sillimanite quartzites, garnet-sillimanite gneisses, marbles, calc-silicate rocks and garnetiferous amphibolites. Rode (1948) suggested that the gneisses have transformed into charnockites during prograde metamorphism. The gneisses, charnockites and supracrustals are deformed into two phases of tight to isoclinal and recumbent folds, followed by open warps near Hazaribagh. In the area around Parsnath hills and Mathurapur (formerly Madhupur), garnetiferous pyroxene granulite, garnetiferous amphibolites and garnetiferous felspathic schists are seen within granitic gneisses. In Mor valley near Dumka and in Jarmundi area to the northwest, migmatitic biotite gneisses contain large enclaves of amphibolite, calc-silicate rock, felspathic quartzite, fibrolite-biotite gneiss, garnet-sillimanite gneiss, charnockite and pyroxene granulite. Charnockitic gneiss occurs as lenses within hornblende granite gneiss. Cordierite-hypersthene granulite is reported from Auranga-Koel valley. Some bodies of anorthosite, as at Dumka, and of syenite near Jamua are seen. All these enclaves occur in a NW swerving large belt near Dumka. The granulitic assemblages have been metamorphosed under high temperature and pressure during peak metamorphism, but were isobarically cooled at 750°C/4-7kb. Zircons from charnockites have yielded U-Pb upper intercept ages of 1624±5 and 1515±5 Ma, probably indicating the age of peak metamorphism during a short period of isothermal decompression, followed by ~1000 Ma lower intercept age denoting isobaric cooling. Rb-Sr age of syenite near Jamua is about 1450 Ma, corresponding to the main orogenic event in CGC.

### Hesathu-Belbathan Belt

A belt of low-grade rocks of small dimensions, but of wide areal spread, is traceable from Garwa through Hesathu to Belbathan, abutting against the Rajmahal Trap. Rocks of the belt are quartz-mica schist, zoisite-epidote quartzite, micaceous quartzite, calc-silicate rock, dolomitic limestone, bedded chert, tremolite-talc schist and actinolite-chlorite schist. Rarely, a cordierite-phlogopite-chlorite-anthophyllite rock is also seen as in Dumri area. Tremolite schist with magnetite bands, calciphyre and dolomitic limestone are seen near Gore, and similar rocks are seen near Garwa. Hesathu-Belbathan belt is noted for sulphide mineralisation. The mineralised host rocks of tremolite-actinolite schist, calc-silicate rock, bedded chert and quartzite are studied near Baraganda and Phaga. This low-grade belt is correlated with the Bhopali Group of Betul belt that is also known for significant sulphide mineralisation.

### Bihar Mica Belt

Detailed mapping of this commercially important mica belt was carried out by L.A.N. Iyer between 1939 and 1944, followed by sectoral studies in various parts of the belt by Geological Survey of India and by Atomic Energy Department (Mahadevan, 2002). Their studies show that the mica belt consists of pelitic schists, quartzites, calc-silicate rocks, para-amphibolites and subordinate carbonate rocks, belonging to Kodarma Group. Quartzites preserve cross-bedding at places. Conglomerates are rare as seen at Inderwa in the east of Kodarma and may have formed the base, but are now dismembered by deformation. Calc-silicate rocks containing zoisite, diopside and hornblende are subordinate. The pelitic schists are essentially biotite-muscovite schists with varying proportions of garnet, staurolite, andalusite, kyanite, cordierite and sillimanite suggesting P-T conditions near the alumino-silicate triple point. Pelitic rocks are highly migmatised, containing palaeosomes of biotite-muscovite gneiss and neosomes of quartzofelspathic material. Dunn (1942) called them as 'diabrochites' that correspond to the definition of metatexitic migmatites. Significantly, granitic rocks constituting about 30 to 40% of the mica belt occur as closely spaced phacolithic or domal bodies and were called as Dome Gneiss in earlier literature. These are mainly peraluminous monzonites containing enclaves of tonalites and other supracrustal rocks. Rapakivi granites are locally seen. Pegmatites intruding the pelitic schists host important mica deposits and hence the name of mica belt. A few late REE-rich pegmatites are potential sources of radioactive minerals.

Broadly, three phases of deformation are encountered in the mica belt. The tight isoclinal folds on E-W axes formed during the early two phases of deformation have caused interference patterns in the form of domes, basins and hook-shaped folds. The third phase of deformation was weak and less extensive. Granite emplacement was controlled by the early two phases of deformation. Late tectonic granites are involved in the third deformational phase, and some of them host lithium mineralisation. Bihar mica belt is correlated with the Betul belt of CITZ. Towards the west, the supracrustals that abut against the Gondwana basin in Ramanujganj area have calc-silicate rocks containing vesuvianite, wollastonite etc. signifying low pressure metamorphism.

### Munger Belt

Supracrustal rocks of Munger Group forming inselbergs in the Gangetic plains form two main outcrops in Rajgir hills near Gaya and Kharagpur hills further east near Bhagalpur. Rajgir hills expose a variety of quartzites showing abundant sedimentary structures like cross bedding, graded bedding, ripple marks and mudcracks. Laminated slates, phyllites and mica schists as well as para-amphibolites underlie the quartzites. The general structure is of two parallel canoe folds lying *en echelon* on ENE trend. Palaeocurrent studies have shown the provenance to be in the northeast.

Kharagpur hills consist of quartzites and phyllites that are deformed into isoclinal folds showing an arcuate disposition from E-W in the south to N-S in the north, as a result of two phases of deformation. The quartzites preserve a variety of sedimentary structures. These belts have been assigned to a younger Munger Group due to K-Ar ages of 360-420 Ma but these may only reflect younger thermal events. On the basis of probable strike continuity, Munger Group may be correlated with the Bijawar Group. Some authors have, however, equated Munger Group with the Mahakoshal Group of CITZ.

### Younger Intrusions

A host of intrusions like gabbro-anorthosites, gabbros, norites, dolerites and some amphibolites, mostly concordant with the foliation of country rocks, is seen throughout the Chhotanagpur Gneiss, but has not been studied in detail. Among these intrusions, ferrogabbros and meta-dolerites with corona structures are abundant and conspicuous. Some dykes are characterised by iron-rich olivine (hortonolite). The most characteristic feature of dykes with corona structures or 'coronites' is the presence of single or double-ply coronas around olivine grains in contact with plagioclase. Other coronas are made of garnet encircling pyroxene and biotite around iron ore or spinel. Coronites are characterised also by the clouding of plagioclases caused by fine inclusions of iron ore, spinel or pyroxene. Their occurrence in the amphibolite-granulite facies transition zone at Palamau, Parasnath, Mathurapur and Dumka is significant, since similar basic dykes are also seen in the granulite transition zone in the Western Dharwar Craton.

*Anorthosite-gabbro*: The anorthosite-gabbro intrusions occurring in the upper amphibolite to granulite areas of Chhotanagpur Gneiss (CGC) are seen at Bela, Chatra and Buchiatamar in the north between Gaya and Patna, at Debaur near Gopalpur in Bihar mica belt, and Dumka, Hinzla, Kauria and Biwabathan in the Hazaribagh-Dumka granulite belt. The well known Saltora (Bankura) anorthosite (called Bengal anorthosite in literature) also forms part of the suite in the Gumla-Purulia granulite belt at the eastern margin of CGC. Bengal anorthosite dated at 1550 Ma occurs as a tadpole-shaped pluton of massif anorthosite (250 km$^2$) consisting of grey, white and mottled anorthosite probably derived from batch melting of tholeiitic magma source. It is probably emplaced at 630-750°C/6±1 kb (Mukherjee et al. 2005). Bela anorthosite consists of white anorthosite, grey gabbroic anorthosite and melanocratic gabbro (Mukherjee and Ghose, 1992). Ultramafic intrusions and some syenites are also frequently associated with these basic intrusions.

### *Alkaline Rocks*

Syenite, nepheline syenite, alkaline granite, carbonatite and apatite-magnetite rock are reported from the southern margin of Gondwana basin of Santuri, Kushunda and Richughuta and along the Tamar-Poropahar shear zone. Peridotite, lamprophyre and dolerite of Gondwana times are also noticed in CGC.

### Tectonic Evolution

The evolution of Chhotanagpur Gneiss (CGC) with North Sighbhum Orogen (NSO), which essentially consists of tonalite-granodioritic gneisses and supracrustal belts bounded by shear zones and boudin-type granulite belts, parallels that of CITZ. The CITZ occurs athwart the structural trends of the Kotri-Dongargarh and Sonakhan belts of Bastar craton just as the CGC and NSO are athwart the trends of Koira/Dhanjori Groups of Singhbhum craton. The main orogenic events in CGC, comparable with that of CITZ, are 1500-1600 Ma in the northern part and 1000-1100 Ma in the southern part, corresponding respectively to the Satpura I and Satpura II orogenies of Acharyya (2001). The details of tectonic evolution in CGC could not be worked out more fully in comparison with CITZ, mainly because the supracrustal rocks occur here as enclave trails rather than coherent belts. The correlation of shear zones and granulite belts of CGC with the CITZ is somewhat tenuous, and the overall database in CGC in respect of these tectonic units is rather sketchy.

## NORTH EAST INDIA

The eastern extension of Chhotanagpur Gneiss beyond the Bengal basin and Rajmahal Trap is seen in North East India (Fig.4S-9) in three areas viz., (i) Shillong or Meghalaya Plateau (1960 m high), that is separated from the alluvial plains of Bangladesh by Dauki Fault, (ii) Mikir Hills Plateau (1360 m high), separated from the Shillong Plateau by Kopili River valley that separates Upper and Lower Assam, and (iii) isolated inselbergs in the Brahmaputra valley, as at Goalpara, Kamrup, Dhubri etc. Geology of these areas is not too well known due to remoteness and inaccessibility. Brief reviews of regional geology have appeared from time to time (Chowdhury and Narayana Rao, 1975; Gogoi, 1975; Mazumder, 1976, 1986; Nandy, 1999; Acharyya, 2001; Ghosh et al. 2005). A broad division of geological units of this terrain is given below:

1. Porphyritic and Non-Porphyritic Granite (Nongpoh, Mylliem, Kyrdem)
2. Khasi Epidiorite or Greenstone
3. Shillong Group
4. Gneisses with enclaves of Older Metamorphic Group (OMG)

### *Older Metamorphic Group (OMG)*

OMG is the name given by early geologists for the enclave suite of ancient

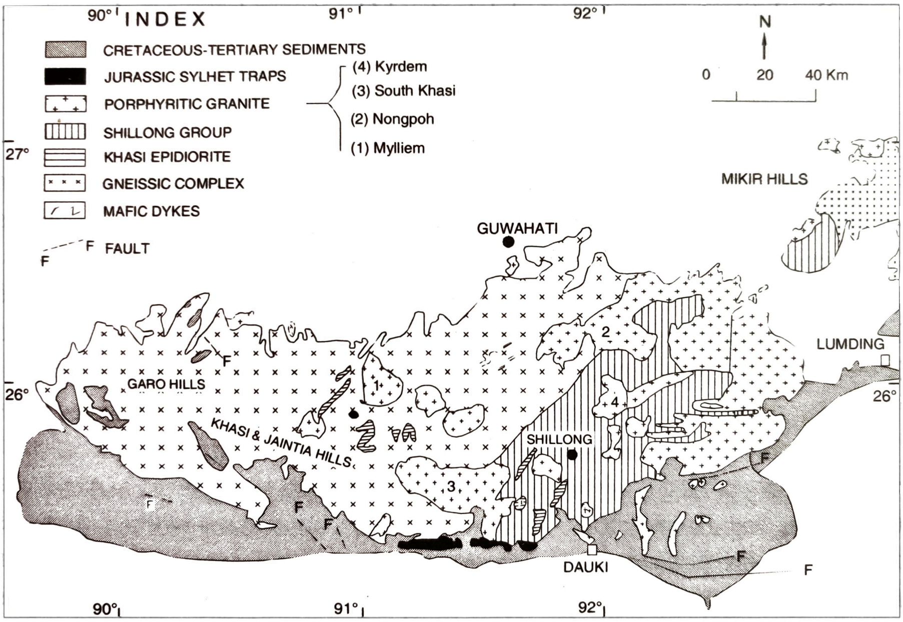
90°
91°
92°
INDEX
CRETACEOUS-TERTIARY SEDIMENTS
JURASSIC SYLHET TRAPS
PORPHYRITIC GRANITE
SHILLONG GROUP
KHASI EPIDIORITE
GNEISSIC COMPLEX
MAFIC DYKES
FAULT
(4) Kyrdem
(3) South Khasi
(2) Nongpoh
(1) Mylliem
N
0 20 40 Km
27°
26°
MIKIR HILLS
GUWAHATI
LUMDING
GARO HILLS
KHASI & JAINTIA HILLS
SHILLONG
DAUKI
F
1
2
3
4

**Fig.4S-9.** Geology of Shillong (Meghalaya) Plateau (after Mazumder, 1976).

supracrustal rocks, which are best exposed in the western part of Khasi and Jaintia hills. The enclave suite consists of following rocks:

*Cordierite-biotite (±sillimanite) gneiss:* This gneiss consists of variable proportions of cordierite, biotite, sillimanite, garnet, sodic plagioclase, microcline and quartz. Cordierite is locally porphyroblastic. The cordierite gneiss occurs as small lenticular bands in biotite gneisses.

*Quartz-sillimanite schist*: This schist forms a coherent belt near Sonapahar, besides occurring as numerous lenticular bands in biotite gneisses. Sillimanite occurs as acicular needles and prisms and has been mined in the past. Topaz, rutile, pyrite and magnetite are usual accessories, whereas biotite and microcline are seen in subordinate amounts. Lenses of sillimanite-corundum rock are also associated with the quartz-sillimanite schist and are interpreted as palaeosol (Golani, 1989). Two bands of dumortierite-tourmaline-quartz schist are exposed at Mawshinrut, where dumortierite occurs as acicular prismatic crystals in the schist.

*Mg-Al pelites:* These unusual magnesian sediments are closely associated with the sillimanite-quartz schist. They contain variable proportions of phlogopite, spinel, anthophyllite, cordierite, sapphirine, chondrodite and corundum, with accessory sphene, rutile, zircon and magnetite. The magnetitehercynite assemblage indicates metamorphic temperature in excess of 850°C, whereas the sapphirine bearing assemblage of Sonapahar yields an estimate of 750°C at 5 kb. The scapolite-plagioclase assemblage in calc-silicate rocks suggests temperature of ~780°C. A decompression path, probably related to continental collision, is proposed for these assemblages. An IBC path is visualised around 550 Ma that represents a widespread thermal event in the area, marked by the well-constrained Rb-Sr age of Nongpoh granite pluton.

These Mg-Al sediments are interpreted as restites after quartzofelspathic material has been squeezed out during migmatization and are known as kinzigites elsewhere. They are interpreted alternatively as products of fluid-absent metamorphism of rocks rich in hydrous minerals like biotite. Many contemporary authors favour the latter origin. The unusual Mg-Al composition has led some workers to propose their origin as palaeosols, but their stratigraphic position is not at the basement-cover interface to favour such an origin.

*Calc-silicate rocks:* These impure carbonate rocks consisting of diopside, garnet, calcic plagioclase, hornblende, epidote and zoisite with accessory sphene, zircon and magnetite, occur as small bands within biotite gneiss.

*Banded Iron Formation:* BIF occurs as numerous lenticular bands in association with mafic rocks at several localities. It contains besides the usual quartz and magnetite, iron rich amphibole (grunerite) and garnet.

*Amphibolites and pyroxene granulites:* These rocks occur as small bands containing hornblende, plagioclase, two pyroxenes and some quartz. They are probably metabasic flows or sills. These are well exposed near Nongstoin in the vicinity of Shillong.

*Charnockites*: Lenses of enderbites are seen within the biotite gneiss near Miji at the foot of Mikir Hills and at a Goalpara inselberg in Assam. These lenses probably link up with the upper amphibolite facies rocks near Sonapahar as part of a boudin-type granulite belt. These are Mesoproterozoic (~ 1600 Ma) in age. Although it is difficult to correlate the granulite belt with those in CGC with such meagre data, it is possible to hazard a guess that this granulite belt and the associated OMG may be similar to the Ramanujganj belt associated with Daltonganj-Dumka granulite belt in CGC.

*Biotite Gneiss*: This forms the widespread country rock. Typically it is migmatitic biotite gneiss, with subordinate augen gneiss and banded gneiss.

Like other grey gneisses of shield areas, it consists of quartz, microperthite, sodic plagioclase and biotite with accessory zircon, sphene, apatite and opaques. Garnet is seen locally. It is essentially an orthogneiss with bands and enclaves of paragneisses of the types described under the Older Metamorphic Group. The Rb-Sr WR age of the gneiss is ~1700 Ma, with younger imprints up to 1150 Ma.

### *Shillong Group*

Shillong Group is essentially a feebly metamorphosed and weakly deformed succession of Proterozoic rocks that overlie the basement biotite gneiss with a distinct unconformity marked by the basal conglomerate near Sumer and Mawsalroh. The succession trends NNE-SSW and has a faulted contact in the south against Sylhet Trap that corresponds to Rajmahal Trap occurring further west. Shillong Group is made of two formations, a lower Mawphlang Quartzite and an upper Mawngup Phyllite. The basal bed is a quartz pebble conglomerate with pebbles almost entirely of vein quartz set in a silty to sandy matrix. Rarely, boulders of metamorphic rocks are seen as clasts. The conglomerates are cross-bedded and grade into quartz arenites. In the area to the north of South Khasi granite, the conglomerate is metamorphosed to higher grades where the matrix contains biotite, garnet and staurolite, as seen at Wa Shora gorge. A major unit of the Mawphlang Quartzite is quartz arenite, which varies from coarse to medium grained sandstone along with siltstone and minor shale. The sandstone consists of grains of quartz and subordinate kaolinised felspar, with fragments of chert and quartzite set in a siliceous matrix. The sandstone is compositionally mature but texturally immature. The siltstone has mainly a sericitic matrix. In areas of higher metamorphic grade, biotite and garnet are grown in the matrix and the rock progressively becomes quartz schist. Dark grey fine-grained quartzite containing calc-magnesian impurities producing tremolite, clinozoisite, calcite, microcline, graphite and pyrrhotite is seen locally. Mawngup Phyllite is a siliceous to carbonaceous phyllite containing quartz, muscovite, graphite and pyrite. In higher metamorphic grades, particularly near the granite plutons, the phyllites and schists contain muscovite, biotite, garnet, chloritoid and andalusite. Some of these rocks are marly and consist of hornblende, garnet, clinozoisite, tremolite, calcite, microcline and oligoclase. Significantly, kyanite is not recorded from these metapelites or marls, suggesting that the overall metamorphism is of low-pressure type.

Preservation of unconformity in weakly metamorphosed sections starkly contrasts with structural conformity and parallelism with South Khasi granite seen in higher grades. This has caused ambiguity in the interpretation of basement-cover relations between Shillong Group and gneissic basement. This ambiguity can be reconciled by the interpretation that the structural parallelism and metamorphic upgradation of Shillong Group with the development of garnet, andalusite and chloritoid, has been brought out by the syn- to late tectonic intrusion of South Khasi granite and Mylliem granite.

Structurally also, the Shillong Group and basement gneiss are different. Polyphase deformation of the basement gneiss is defined by compositional layering parallel to early isoclinal fold axes and refolding of this foliation by later deformational events, including late open folding. In Shillong Group, on the other hand, the early foliation is related to intrafolial folds, followed by the major asymmetrical isoclinal folds ($F_2$). The $F_2$ folds have largely controlled the map pattern. $F_3$ folds are open, steeply plunging folds. This contrast in deformation pattern, though not distinctive in absolute terms, is an indication of their difference in relative age. The age of Shillong Group from Pb-Pb age of galena is 1550 Ma (*see* Mitra and Mitra, 2001). However, on broad geological considerations, the Shillong Group may correlate with the Munger Group of CGC.

### *Khasi Epidiorite*

A group of metabasic intrusions, partly concordant and partly discordant, is seen within the Shillong Group and is called Khasi Epidiorite or Khasi Greenstone. The epidiorite encloses xenoliths of Shillong Group and is not involved in the deformation of Shillong Group and hence forms a younger group of intrusions. The epidiorite consists essentially of hornblende needles and plagioclase, at places preserving the cores of original pyroxene and plagioclase laths. Quartz, clinozoisite, ilmenite and some green biotite are seen at places. Dykes of norite intruding the basement gneisses may belong to this magmatic episode.

### *Neoproterozoic Granites*

Four main porphyritic granite plutons are noticed in the craton. They are: (i) Mylliem granite, (ii) Kyrdem granite, (iii) Nongpoh granite, and (iv) South Khasi granite along with its satellite bodies of Kyllang, Rongjeng (800 Ma), Sindhuli (880 Ma) and Mowdoh. These different plutons are late- to post-tectonic with respect to Shillong Group.

Mylliem granite (~600 Ma), an elliptical body covering an area of 40 km$^2$, is one of the earliest studied plutons of the region that intrudes the Shillong Group and Khasi Epidiorite. The pluton consists of porphyritic microcline granite that is interpreted either as a funnel-shaped intrusion or diapir. Kyrdem granite (480 Ma) is a similar pluton occurring to the northeast. South Khasi granite (690 Ma) is a large body (600 km$^2$), which has migmatitic contact with basement gneisses and Shillong Group. These granites are responsible for the higher metamorphic grades in Shillong Group in the contact zones. Nongpoh pluton (550 Ma) is a porphyritic microcline granite intruding the biotite gneiss for the most part and Shillong Group in the southeast. These granites show variable Rb-Sr ages ranging from 480 to 880 Ma, with memories of 1150 and 1500 Ma, and this variation is believed to be due to incomplete isotopic homogenisation. The 550 Ma age of Nongpoh granite statistically matches with the ages of other granite bodies and represents an important thermal event in the region.

### Correlation with Aravalli Craton

Fermor (1936), while dividing the Indian Precambrian into tectonic provinces, suggested a possible link between the Satpura belt and the Aravalli craton to the east of the shear/thrust zone between Aravalli and Delhi Supergroups. Yedekar et al. (1990) and most subsequent workers (including Leelanandam et al. 2006) have adopted this division. Fermor (1936) extended the CISZ to the Delhi-Marwar craton contact, whereas Yedekar et al. (1990) equated CISZ with the Aravalli-Delhi contact. Such a correlation may be broadly acceptable, but there are incongruities in points of detail, which are discussed below. In order that these details are better understood, the section on Aravalli craton (Chapter 3) may be referred to.

In conformity with some of the recent classifications of the Aravalli craton, the SONA North Fault (SNNF) may correlate with the Great Boundary Fault of Rajasthan. Hindoli belt with Mahakoshal belt, Banas Dislocation Zone (Jahazpur Thrust) (*see* Sinha-Roy et al. 1995) with SONA South Fault (SNSF), Mangalwar Complex and mineralised belts with the gneissic complex and Betul belt of CITZ, Kaliguman Fault with Tan Shear Zone, Sandmata granulite belt with Ramakona-Katangi granulite belt, Lunavada-Champaner-Delhi sequence with the Sausar Group and Phulad Lineament corresponds to CISZ.

The correlation of Sausar Group with the Lunavada-Champaner-Delhi sequence is mainly based on the occurrence of manganese in Jhabua in Madhya Pradesh and Champaner Group in Gujarat. The Sausar Group is mainly an orthoquartzite-pelite-carbonate association, which is similar to Delhi Supergroup. The Aravalli Supergroup, dated between 2100 and 1800 Ma, is deposited on an Archaean (3300-2900 Ma) granitic basement and corresponds to Sakoli and Chilpi Groups of CISZ. There is yet another suggestion that the Ambaji-Sendra belt with its comparable sulphide mineralisation may correlate with Betul belt, but this needs further study for confirmation. The suggested correlation (Table 4S-6) is therefore only tentative, based on incomplete information in a vast terrain dissected by numerous faults and associated granulite belts and where critical linkages are lost under a large cover of younger rocks like Deccan Trap, Gondwana sediments and Holocene alluvium.

**Table 4S-6.** Comparison between Aravalli craton and CITZ

| Aravalli craton | CITZ |
|---|---|
| Great Boundary Fault | SNNF |
| Hindoli belt | Mahakoshal belt |
| Jahazpur Thrust | SNSF |
| Mangalwar Complex and Pb-Zn belts | Betul belt and gneisses with mineralised belts |
| Kaliguman Lineament | Tan shear zone |
| Sandmata granulite belt | Ramakona-Katangi granulite belt |
| Lunavada-Champaner-Delhi belt | Sausar belt |
| Phulad Lineament against Marwar craton | CISZ |
| Aravalli belt on Mewar craton | Sakoli-Chilpi belts on Bastar craton |

### Correlation of different sectors of Satpura Mobile Belt

Satpura mobile belt occurs in four major sectors from west to east viz., Aravalli Craton, CITZ, Chhotanagpur Gneiss (including the North Singhbhum Orogen or NSO) and Meghalaya (Shillong) Plateau (Fig.4S-10). A tentative correlation chart of the different sectors of Satpura mobile belt is given in Table 4S-7. The chart shows that the Satpura mobile belt consists of supracrustal belts set within the gneissic complex dissected by shear zones and granulite belts. Distribution of deformed alkaline rocks and carbonatites (DARC) as well as anorthosite bodies, and their relation to major shear zones is too poorly known to identify sutures within the mobile belt (Leelanandam et al. 2006). A comprehensive picture of evolution of the mobile belt in different sectors will have to await detailed geological mapping combined with geochronology using different isotopic systematics.

The present data, however, show that SMB evolved around 1800-2000 Ma as a rift on continental crust with Mahakoshal and Hindoli deposition in the north. Aravalli, Sakoli, Chilpi and Singhbhum (NSO) deposition started in the south on Mewar, Bastar and Singhbhum cratons. The oceanic crust that formed in the middle was subducted to produce island arcs. The arcs marked by Mangalwar-Sandmata Complex, Tirodi-Amla Gneiss and central

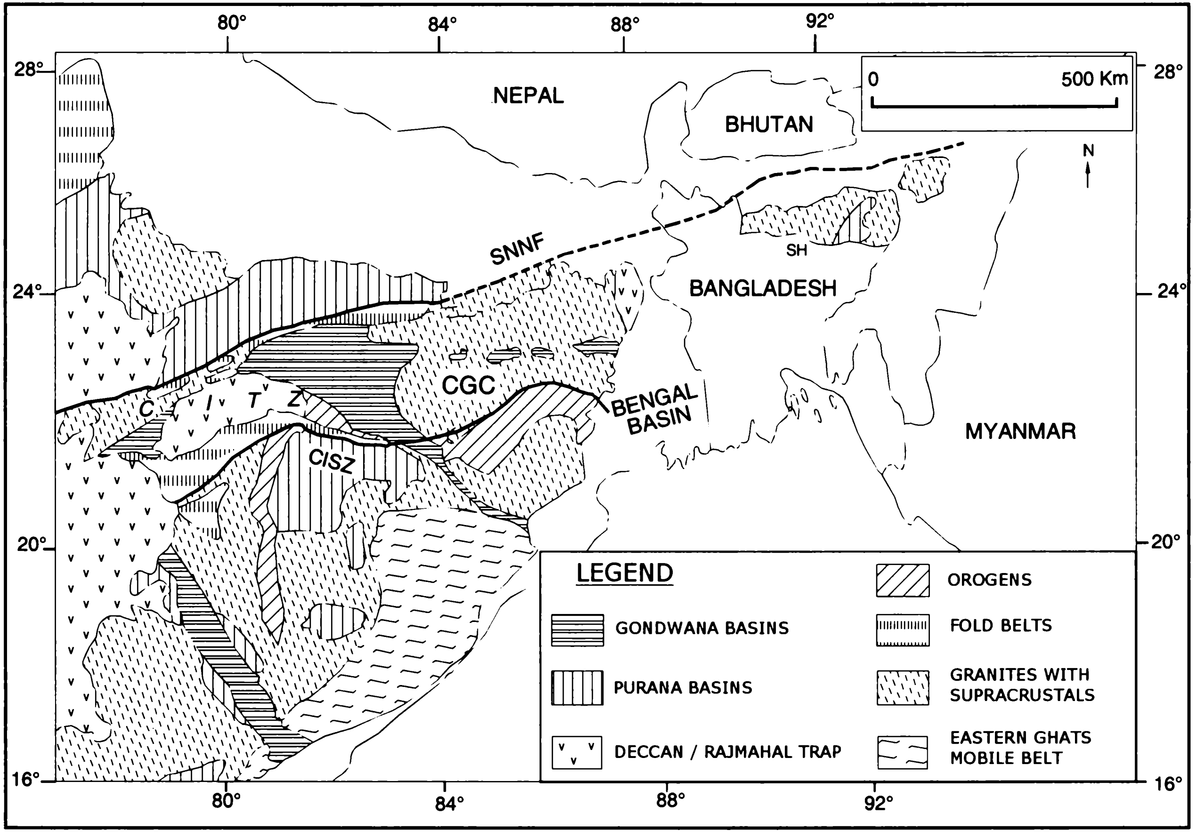
80°
84°
88°
92°
28°
24°
20°
16°
0
500 Km
N
NEPAL
BHUTAN
BANGLADESH
MYANMAR
SNNF
SH
CGC
C I T Z
CISZ
BENGAL BASIN
LEGEND
GONDWANA BASINS
PURANA BASINS
DECCAN / RAJMAHAL TRAP
OROGENS
FOLD BELTS
GRANITES WITH SUPRACRUSTALS
EASTERN GHATS MOBILE BELT

**Fig.4S-10.** Geological map showing the disposition of the CITZ, CGC and Shillong (SH) plateau (after Acharyya, 2003). SNNF - Son-Narmada North Fault. CISZ - Central Indian Shear Zone.

Chhotanagpur Gneiss around 1500-1600 Ma were followed by intra-arc and back-arc sedimentation of Bhilwara, Betul and Kodarma sequences, as well as Lunavada-Champaner-Delhi, Sausar and Ranchi-Gangpur-Kunjar basins. The final closure of SMB at ~1000 Ma is responsible for the present configuration of the mobile belt.

**Table 4S-7.** Tentative correlation chart of Satpura Mobile Belt

| Aravalli Craton | CITZ | Chhotanagpur Gneiss/ NSO | NE India |
|---|---|---|---|
| Vindhyan | Vindhyan / Bijawar | Munger Group | Shillong Group |
| GBF | SNNF | SNNF | Brahmaputra Fault |
| Hindoli | Mahakoshal | Mahakoshal | — |
| Jahazpur Thrust | SNSF | SNSF | |
| Mangalwar Complex and Bhilwara Group; | Amla Gneiss with Golighat Group | Bihar Mica belt | Gneiss with OMG |
| Rajpura-Dariba belt etc. | Bargaon and Bhopali Groups | Hesathu-Belbathan belt | — |
| Kaliguman shear zone | Tan shear zone | North Purulia shear zone | Shillong granulites |
| Sandmata Complex | Ramakona-Katangi granulite belt | Hazaribagh-Dumka granulite belt | |
| Lunavada-Champaner-Delhi sequence | Sausar belt | Gangpur, Kunjar, Ranchi | |
| Pilwa-Chinwali granulite belt | Balaghat-Bhandara granulite belt | Gumla-Purulia granulite belt | — |
| Phulad shear zone | CISZ | Tamar-Poropahar shear zone | Phanerozoic Dauki Fault |
| Aravalli belt on Mewar craton | Sakoli (?) and Chilpi Groups on Bastar craton | Singhbhum Group on Singhbhum craton | |

# PRECAMBRIAN OF HIMALAYA

## INTRODUCTION

The Himalaya 'is a colossus among the great mountains of the world' and aptly called 'the king of mountains' (Nagadhiraj) by the renowned poet Kalidasa. The mighty Himalaya forms part of the Alpine-Himalayan chain of mountains that stretch from Spain in the west to Indonesia in the east, and includes the Baltic, Carpathian, Zagros, Hindukush and Arakan Yoma mountains. The Himalaya *sensu stricto* represents the large orogenic belt that covers a length of 2500 km and width of 300-400 km, bounded by the syntaxes or knee-bends of Nanga Parbat (8126 m) in the west and Namche Barwa (7256 m) in the east. Westward of the Nanga Parbat syntaxis, the extensions of Himalaya are seen along the Sulaiman and Kirthar ranges of Pakistan, ending against the Arabian Sea and covering a total length of 5200 km (Fig.4H-1a). The Himalayan orogenic belt has an arcuate trend from NW to NE with convexity to the south. Major crustal scale faults terminate the orogen against the adjacent tectonic units, like the eastern Mishimi fault against the Arakan Yoma orogenic belt that includes the Andaman-Nicobar islands, and the western Chaman Fault that joins the Owen Fracture Zone in the Arabian Sea. The mountains are famous for the tallest peak of the world in Mount Everest (8850 m) and have other celebrated peaks of Kanchanjunga (8598 m), Dhaulagiri (8172 m), Nanda Devi (7817 m), Kedarnath (6900 m), Badrinath (7138 m) etc. The Himalaya is among the youngest mountains of the world that is still growing. It is a product of India-Asia plate tectonic collision, and is a classical example of continent-continent collision in the world.

Traditionally, the Himalaya is divided geologically into six zones, which are, from south to north, as follows (Fig.4H-1b):

1. Sub-Himalaya or Outer Himalaya (or Siwalik Terrane) consisting of molasse sediments (18 to 1 Ma) exposed in the Siwalik Hills (250-800 m thick), together with their intermontane valleys called the *duns* (e.g., Dehra Dun). The molasse sediments form an apron of gravelly debris in the middle called the *Bhabar*. The Outer Himalaya is bounded to the south by the Himalayan Frontal Thrust (HFT), separating it from the vast Holocene Indo-Gangetic Alluvium of the Sindhu-Ganga Trough.
2. The Lesser or Lower Himalaya overthrusts the Sub-Himalaya in the south

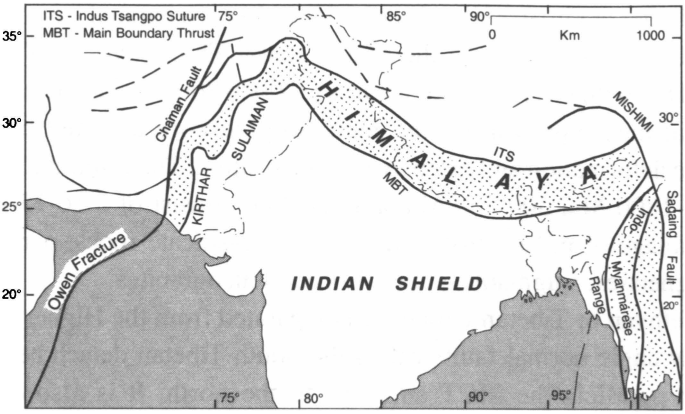
ITS - Indus Tsangpo Suture
MBT - Main Boundary Thrust
75°
85°
90°
0
Km
1000
35°
30°
25°
20°
Chaman Fault
SULAIMAN
KIRTHAR
HIMALAYA
ITS
MBT
MISHIMI
Indo-Myanmarese Range
Sagaing Fault
Owen Fracture
INDIAN SHIELD
75°
80°
90°
95°
30°
20°

**Fig.4H-1a.** Geographic boundaries of the Himalaya (Valdiya, 1998).

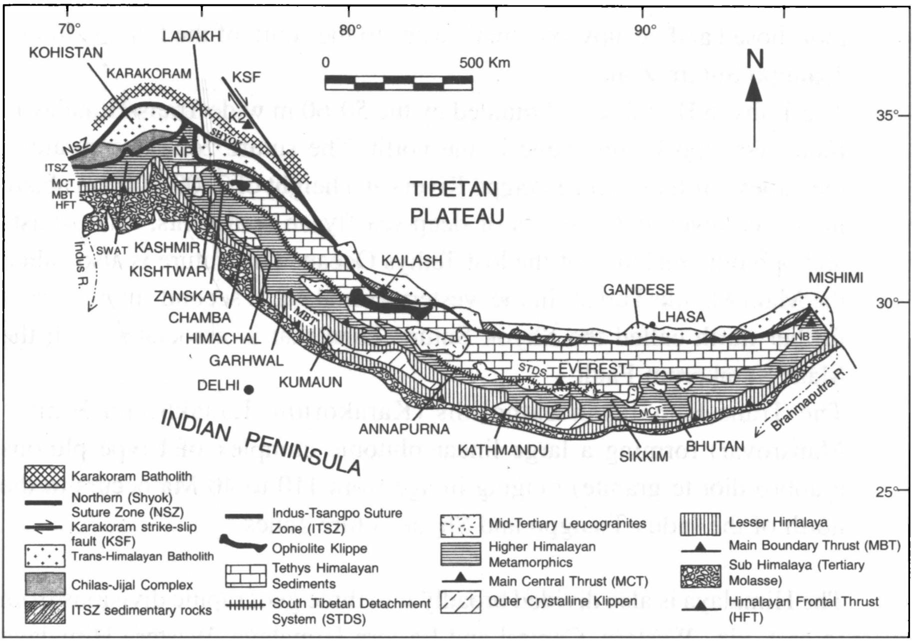
70°
80°
90°
0
500 Km
N
35°
30°
25°
KOHISTAN
LADAKH
KARAKORAM
KSF
K2
SHYOK
NSZ
NP
ITSZ
MCT
MBT
HFT
Indus R.
SWAT
KASHMIR
KISHTWAR
ZANSKAR
CHAMBA
HIMACHAL
GARHWAL
DELHI
KUMAUN
TIBETAN PLATEAU
KAILASH
GANDESE
LHASA
MISHIMI
NB
STDS
EVEREST
MCT
MBT
Brahmaputra R.
ANNAPURNA
KATHMANDU
SIKKIM
BHUTAN
INDIAN PENINSULA
Karakoram Batholith
Northern (Shyok) Suture Zone (NSZ)
Karakoram strike-slip fault (KSF)
Trans-Himalayan Batholith
Chilas-Jijal Complex
ITSZ sedimentary rocks
Indus-Tsangpo Suture Zone (ITSZ)
Ophiolite Klippe
Tethys Himalayan Sediments
South Tibetan Detachment System (STDS)
Mid-Tertiary Leucogranites
Higher Himalayan Metamorphics
Main Central Thrust (MCT)
Outer Crystalline Klippen
Lesser Himalaya
Main Boundary Thrust (MBT)
Sub Himalaya (Tertiary Molasse)
Himalayan Frontal Thrust (HFT)

**Fig.4H-1b.** Tectonic divisions of the Himalaya (modified after Gansser, 1981).

along the Main Boundary Thrust (MBT). The Lesser Himalaya has an undulating landscape in the middle and mountainous terrain on the sides like Pir Panjal and Dauladhar ranges (3500 m) in Kashmir and Mahabharat Hills (3000 m) in Nepal. This zone contains Palaeoproterozoic (~1800 Ma) and lower Palaeozoic (~500 Ma) sediments some of which are metamorphosed up to greenschist facies. This zone also contains cappings of Tertiary sediments, nappes and *klippen* of metamorphic rocks (2200 to 1800 Ma) and Pan African granitic intrusions (~550 Ma).

3. The Higher or Greater Himalaya (or Himadri) is separated from the Lesser Himalaya in the south by the Main Central Thrust (MCT). The Higher Himalaya with its high rugged scarps (3000 to 8000 m) consists of Central Crystallines representing the metamorphic core affected by intense ductile deformation and extensive migmatisation. The Central Crystallines (2200-1800 Ma, 500-550 Ma and ~20 Ma) consist of a 10-15 km thick assemblage of mica schists, quartzites, calc-silicate rocks, paragneisses, orthogneisses, migmatites, and Miocene leucogranites.
4. The Tethyan or Tibetan Himalaya is separated from the Higher Himalaya by low angle normal faults called the South Tibetan detachment system which parallels the MCT and dips to the north. It is also called the Trans-Himadri Thrust. The Tethyan Himalaya has 10-17 m thick succession of highly fossiliferous marine sediments of Neoproterozoic (~600 Ma) to Eocene (~65 Ma) ages. The sediments are largely unmetamorphosed and occupy synclinal basins to the south of the famous Indus-Tsangpo Suture Zone.
5. The Tethyan Himalaya is bounded by the 50-60 m wide Trans-Himalayan Indus-Tsangpo Suture Zone in the north. The suture zone occurs along the valleys of Indus and Tsangpo Rivers at a height of 3500-5000 m above mean sea level and consists of deep-sea flysch sediments, blue schists and ophiolite mélange of the lost Tethys Ocean. This suture is also called the Main Mantle Thrust. In the western Himalaya, a second suture occurs further north called the Shyok Suture Zone that is associated with the Main Karakorum Fault.
6. The Trans-Himalayan batholiths (Karakorum, Ladakh and Kailas-Mansrovar) forming a large linear plutonic complex of I-type plutons (gabbro-diorite-granite) ranging in age from 110 to 40 Ma occurs to the north of the Indus-Tsangpo and Shyok suture zones.

The Himalaya is also divided broadly into three geographic divisions from west to east, viz., Western, Central and Eastern Himalaya. Western Himalaya encompasses Jammu and Kashmir (Ladakh, Zanskar, Pir Panjal and Dauladhar ranges), Himachal Pradesh, Uttarakhand (Kumaun and Garhwal Hills) and the adjoining Karakoram, Kohistan, Kailas and Mansarovar ranges. Central Himalaya essentially covers Nepal. Eastern Himalaya includes Darjeeling (Bengal), Sikkim, Bhutan and Arunachal Pradesh.

### Previous Studies

Vast literature exists on the classical geology of the Himalaya. Recent summaries of Himalayan geology are available in the following publications:

**Table 4H-1.** Precambrian Stratigraphy and Correlation of the Himalaya

**LESSER HIMALAYA**

| Cycle and Approx. Age | Jammu and Kashmir | Himachal Pradesh | | | Uttarakhand | Nepal | Sikkim - Darjeeling | Bhutan | Arunachal Pradesh |
|---|---|---|---|---|---|---|---|---|---|
| Eocambrian | Sincha Fm. | Tal Gp. | | Milan Gp.<br>(Tethyan part) | — | Tistung Gp. | — | — | — |
| Cycle IV<br>570-700 Ma | Bhimdasa Fm.<br>Macchal Fm.<br>Ramsu Fm. | Krol Group<br>Blaini Group | | | | Nawakot Gp.<br>(Upper) | | Diuri Fm. | Dedza Fm. |
| Cycle III<br>~1000 Ma | Ramban Fm.<br>(Sauna volc.)<br>Gamir, Baila Fm. | — | Simla Gp.<br>(Tattapani volc.) | Jaunsar Gp.<br>(Peontra volc.) | | Nawakot Gp.<br>(Lower) | Gorubathan Fm.<br>Baxa Gp. | | Dirang Gp. |
| Cycle II<br>1200-1500 Ma | Kalamund Fm. | Larji Gp. | Shali Gp. | Deoban Gp. | | Dailekh Gp.<br>Jaljala Gp. | | Baxa Gp. (?)<br>Shumar Fm. | Bomdila Gp. |
| | Befliaz Fm. | Rampur Gp.<br>(Banjar volc.) | Sundernagar Gp.<br>(Mandi volc.) | Dharagad Gp.<br>(Atal volc.) | Garhwal Gp.<br>(Rautgara, Tejam, Berinag, Pithoragarh, Naraul, Bhowali Gps.) | Kathmandu Gp.<br>Pokhara Gp. | Daling Gp. | Jaishidanda Fm. | |
| Cycle I<br>1800-2250 Ma | | Wangtu, Bandal Gneiss | | Almora, Askot, Baijnath and Dharamgarh Gneiss | Annapurna Gneiss | Lingtse Gneiss<br>Darjeeling Gneiss | Thimphu Group | Ziro Gneiss | |

**HIGHER HIMALAYA**

| Cycle and Approx. Age | Jammu and Kashmir | Himachal Pradesh | | | Uttarakhand | Nepal | Sikkim - Darjeeling | Bhutan | Arunachal Pradesh |
|---|---|---|---|---|---|---|---|---|---|
| Cycles<br>IV and III | Karihul Fm.<br>Lolab Fm. | Kunzum La Fm.<br>Batal Fm. | | Manjir Fm.<br>Bhaderah Fm. | Martoli Fm.<br>Dudatoli Fm. | Dhauladhar Gp. | — | Mao Khola Gp. | Lum La Fm. |
| Cycle II | Salkhala Gp.<br>(with Tanawal Fm.) | Chamba Fm.<br>Salkhala Gp.<br>(with Tanawal Fm.) | | Kulu Gp.<br>Jutogh Gp. | Haimanta Gp. | Bhimpedi Gp. | — | — | — |
| Cycle I | Nanga Parbat Gneiss | Vaikrita Gp.<br>Suru, Giambal, Rohtang<br>Tso Morari Gneiss | | | Vaikrita Gp.<br>(Central Crystallines) | Himal Gp. | Kanchenjunga Gneiss | Thimphu Gp. | Se La Gp. |

Gp. - Group; Fm. - Formation; volc. - Volcanics

Gansser (1964, 1981, 1983, 1991), Sharma (1977), Saklani (2006), GSI (1989), Sinha (1989, 1992), Thakur (1993), Bhargava (1995), Srikantia and Bhargava (1998), Gopendra Kumar (1997, 2005), Valdiya (1998), Bhargava and Bassi (1999), Jain and Manickavasagam (1999) and Macfarlane et al. (1999).

## STRATIGRAPHY

The Precambrian sequences of the Himalaya are exposed mainly in the Lesser and Higher Himalaya and to a lesser extent in the Tethyan Himalaya and Trans-Himalaya. The stratigraphy is complicated by the lack of fossils in the Precambrian and Phanerozoic unmetamorphosed sections, disruption by large-scale faults and thrusts, overprinting by Himalayan orogeny involving Tertiary metamorphism and granitic intrusions, and lack of adequate radiometric ages. In a major regional synthesis, the Geological Survey of India has divided the lithostratigraphy into eleven sedimentary cycles. Out of these, Cycles I to IV (First to Fourth Cycles) pertain to the Precambrian (Table 4H-1), extending from Palaeoproterozoic to the Eocambrian (GSI, 1989). Some of these cycles are classified into *supersequences.* There are no recognisable Archaean elements in the Himalaya, and so its early history commences with the Palaeoproterozoic basement of the Indian shield. The Precambrian stratigraphic description of Himalaya is organized here according to sedimentary cycles belonging to different tectonic zones (like the Lesser and Higher Himalaya), and categorised into geographic regions in the Western, Central and Eastern Himalaya.

### First Cycle

A generalized lithostratigraphy of the First Cycle, based on well-developed sections in Kumaun, is given below (Table 4H-2).

**Table 4H-2.** Composite lithostratigraphy of the First Cycle

| |
|---|
| Intercalated quartzite, mica schist, marble, calc-silicate rock, metabasic rock, biotite gneiss and younger granite (chlorite to biotite grade) |
| Mica schist, quartzite, migmatitic biotite gneiss, granitic gneiss and basic sills (biotite grade) |
| Garnet-mica schist, quartzite, calc-silicate rock, banded and augen gneiss (garnet grade) |
| Kyanite schist, garnet-biotite-staurolite schist and quartzite, biotite gneiss (staurolite-kyanite grade) |
| Sillimanite-muscovite-K-felspar gneiss (sillimanite grade) |

### *Higher Himalaya: Central Crystallines*

The oldest lithological unit forming the basement complex consists of 10-15 m thick para- and orthogneisses and other supracrustals called the *Central Crystrallines* in the Higher Himalaya. The Central Crystallines represent the metamorphic core of the Himalaya and forms the axis of maximum uplift in the orogenic belt. They are exposed prominently in Himachal Pradesh and Uttarakhand, the best studied section being along the Kali and Gori areas of Kumaun. They are known by different local geographic names along the length of the Himalaya, such as Zanskar Crystallines, Nanga Parbat Crystallines etc.

*Nanga Parbat Crystrallines* in Jammu and Kashmir represent the most northerly outcrop of Indian continental crust within the Himalayan orogen. The basement complex metamorphosed under upper amphibolite facies represents metapelites, metagreywackes, rare calc-silicate rocks, and granitic gneisses. Migmatites, locally cut by metabasic sheets, are common. Three phases of deformation are recognised, viz, tight to isoclinal, intrafolial folds ($F_1$), superposed by large, E-W trending kink folds ($F_2$) and large N-S trending antiforms ($F_3$). Zircons from the gneisses have yielded U-Pb ages of 1800-2200 Ma, along with *vestiges* of some older Neoarchaean (2500-2700 Ma) protolithic components. Typical metapelites contain quartz, biotite, sillimanite, K-felspar, and plagioclase, and variable amounts of garnet, cordierite, spinel and muscovite. Cordierite seams consisting of K-felspar, quartz and dark nodular masses of cordierite are probably restites produced by localised incongruent melting of biotite in the presence of a fluid at 630° C and 4 kb. Tourmaline-bearing two-mica leucogranites (e.g., Tato pluton) intruding the basement complex have probably originated by vapour-absent muscovite melting at ~720° C at 7-8 kb, corresponding to depths of 20-25 km. These granites appear to be among the youngest plutons (10-18 Ma) of Higher Himalaya.

*Tso Morari Crystallines* (TMC) of Ladakh (Kashmir) belong to the *Trans-Himalayan Zone* and are exposed in an elongate NW-plunging dome with a 100 km long axis. TMC consists of quartzo-felspathic gneisses and metasediments, along with Palaeozoic intrusive granitoids. Three phases of deformation are recorded in TMC, viz., early NW-SE trending isoclinal folds, followed by coaxial open to tight folds, and the later NE-SW trending open folds. Garnetiferous quartzofelspathic gneisses with lenses of eclogite are included in the Puga Formation (Palaeoproterozoic) that is correlated with the Central Crystallines. About 25 eclogite lenses and sills are mapped within the TMC and represent ultrahigh pressure (UHP) metamorphism along the leading edge of the Indian plate at a depth of ~100 km around 55 Ma. Younger granites (~460 Ma) intrude the Tso-Morari dome.

*Suru-Giambal (Zanskar) and Rohtang Crystallines* of Himachal Pradesh belong to Vaikrita Group. They are exposed in two important and independent antiforms of the basement complex. The Suru-Giambal gneiss extends for 200 km from Lahaul in Himachal Pradesh to Sanko in Ladakh, and consists of two units. The lower unit is made of banded quartzofelspathic gneiss and garnet-staurolite-kyanite-sillimanite gneiss having interbands of amphibolite and cordierite-anthophyllite gneiss. The upper unit consists of quartz-biotite-muscovite schist, amphibolite, quartz-muscovite schist, calc-phyllite and marble. Migmatitic gneiss consists of melanocratic palaeosome of garnet-staurolite-mica schist and neosome of leucocratic quartz-felspar gneiss. Pegmatites and aplites containing tourmaline intrude the mica schists. Wangtu gneiss of Vaikrita Group has Rb-Sr age of 2025±86 Ma. *Rohtang gneiss* consists of a series of layered psmammitic gneisses and mica schists of great thickness exposed for 250 km between the Chanderbhaga and Sutlej river valleys, in a NW plunging antiform. Unlike in other parts of Central Crystallines where metamorphic inversion is noticeable, here the metamorphism is reported to be progressive in the normal order from chlorite to sillimanite grade (Srikantia and Bhargava, 1998, p.192). The temperature range of progressive metamorphic zones is 540°, 560°, 640° and 650°C. Extensive intrusions of granite to granodiorite (Rakcham, Karcham, Mantalai, Manikaran and Gangotri granitoids) of Pan African age (~580 Ma) abound in the Rohtang gneiss. Leucogranites of 14-28 Ma age are also reported.

In Uttarakhand, the Central Crystallines belonging to Vaikrita Group (including Munsiari Formation) extend NW-SE from Kumaun to Garhwal and east of Kullu in Himachal Pradesh. The lithostratigraphic succession of this region is given in Table 4H-2. The dominant gneissic complex with supracrustal enclaves and rafts yields Rb-Sr ages of 1890±155 Ma (Munsiari), 1904±59 Ma (Ramganga), 2047±102 and 1973±102 Ma (Bhagirathi), 2120±60, 1841±86 and 1811±123 Ma (Chail), 2315±135 Ma (Dhakuri) and 1950±200 Ma (Joshimath). A significant feature of this succession is the presence of widespread inverted metamorphism. Munsiari Formation shows the highest grade at 650° C and 7.5 kb that diminishes to lower amphibolite facies (~500° C and 5 kb).

The *Higher Himalayan Crystallines (HHC)* of Nepal are represented by the Himal Group in Dhauladhar and Annapurna ranges. Two crystalline nappes are reported from Eastern Nepal; namely, the Higher Crystalline Sheet and the Khumbhu Nappe, and these are separated by the extension of Vaikrita Thrust.

In the type section at Manaslu, Barrovian high-grade metasediments enclose concordant bodies of granitic gneiss and migmatite, together with younger porphyritic granites. Makalu leucogranite intruding the overlying Tethyan sediments is correlatable with Manaslu granite that has Rb-Sr date of 18 Ma and U- Pb date of 25 Ma.

In the *Eastern Higher Himalaya*, Darjeeling gneiss contains lenses of kyanite-sillimanite gneiss and calc-gneiss. The Kanchanjhunga gneiss of Sikkim, that is the equivalent of Darjeeling gneiss, consists of migmatite and high-grade metamorphics. In Bhutan, similar lithological association of Higher Central Crystallines is called the Thimphu Group that consists of augen gneiss and migmatite with lenses of kyanite-sillimanite schist and quartzite, as well as calc-gneiss.

In Arunachal Pradesh, the HHC consists of the metasediments of Se La Group that are well exposed near Subansiri along the Se La Pass on the Bomdila-Tawang road. Se La Group is a continuation of Thimphu Group of Bhutan and is divided into two formations, the lower unit (Taliha Formation) consisting of calc-silicate marble, graphitic schist, sillimanite gneiss and amphibolite, and the upper unit (Galensiniak Formation) comprising kyanite-sillimanite-staurolite schist and gneiss, quartzite and migmatite. Se La Group is intruded by Pan African hornblende granite and Tertiary tourmaline granite having Rb-Sr isochron age of 28 Ma. In the Siang syntaxis of Arunachal Pradesh, the equivalent of Se La Group is called the Siang Group.

### *Lesser Himalaya: Basement Complex*

The basement complexes of Western Lesser Himalaya are the granites and gneisses of *Kishtwar window* in Kashmir and *Rampur-Larji window* in Himachal Pradesh. These are classified under Jeori-Wangtu and Bandal Groups that consist of basal migmatitic pelitic gneiss, mica schist, quartzite and marble, and the overlying porphyroblastic gneiss, meta-conglomerate and calc-silicate rock. The crystalline thrust stacks of *Almora-Baijnath-Askot-Daramgarh* in Himachal Pradesh and Uttarakhand expose graphitic schist, quartzite, marble and augen to mylonite gneiss belonging to Kullu Group. These rocks extend to Kashmir as Sincha Formation. In the Lesser Himalaya of Nepal the basement gneisses are called Annapurna gneiss, and in Darjeeling they are called Lingtse gneiss.

### Second Cycle

This cycle commences with quartzite-metabasalt association that passes upward into orthoquartzite-carbonate facies. The sequence is topped by a quartzite-slate unit. Penecontemporaneous volcanism is a characteristic feature of this cycle in the lower part. Lateral facies variations, frequent interfingering of formations and interruption by thrusting have caused problems in stratigraphic classification and correlation. The sequence is mostly unmetamorphosed, but for the local development of greenschist facies. Stromatolitic carbonate and phosphorite are common, which may correspond to the global Mesoproterozoic event. Many metalliferous occurrences are located in this cycle. A generalized composite lithostratigraphy of the cycle is given below (Table 4H-3).

**Table 4H-3.** Composite lithostratigraphy of the Second Cycle

| | |
|---|---|
| Quartzite with siltstone and slate | Kalamund (Kashmir) |
| Carbonate sequence with stromatolitic dolomite, phyllite | Shali, Deoban (H.P.) |
| Limestone, phosphorite, magnesite, quartzite | Gangolihat (Kumaun) |
| Quartzite with penecontemporaneous flows of spilite-keratophyre, phyllite | Mandi, Banjar (H.P.) |
| Carbonaceous phyllite, quartzite, metavolcanics and marble | Tenga Formation (Arunachal) |

### *Higher Himalaya*

In the Higher Himalaya of *Kashmir-Chamba* region, the sequence earlier described in literature as Dogra Slate is now classified into three formations: the lower unit consists of quartzite, metabasalt and dolomitic limestone (Bafliaz Fm.), the middle unit contains rhythmite, phyllite, volcanics and local conglomerate (Chandinar and Buniyar Fms.) and, the upper unit comprises quartzite with shale and siltstone (Kalamund Quartzite). In the Higher Himalaya of Sikkim-Darjeeling and Bhutan, the equivalent succession is part of Jaishudanda Formation consisting of quartzite, calc-silicate rock, marble, graphitic schist, and garnet-mica schist with rare amygdular amphibolite.

### *Lesser Himalaya*

In the Lesser Himalaya of *Jammu*, the Second Cycle is probably represented by Riasi Limestone/Jammu Limestone. The most extensive development of this cycle occurs in Himachal Pradesh, where it is well preserved below the crystalline nappes of Larji, Shali and Deoban.

In the *Larji window* (Fig.4H-2), this cycle is represented by an older Rampur Group and a younger Larji Group. The Rampur Group is divided into three formations: the lower unit (Bhallan Fm.) consists of slate, phyllite, flaggy quartz arenite and subordinate metabasalt; the middle unit (Banjar

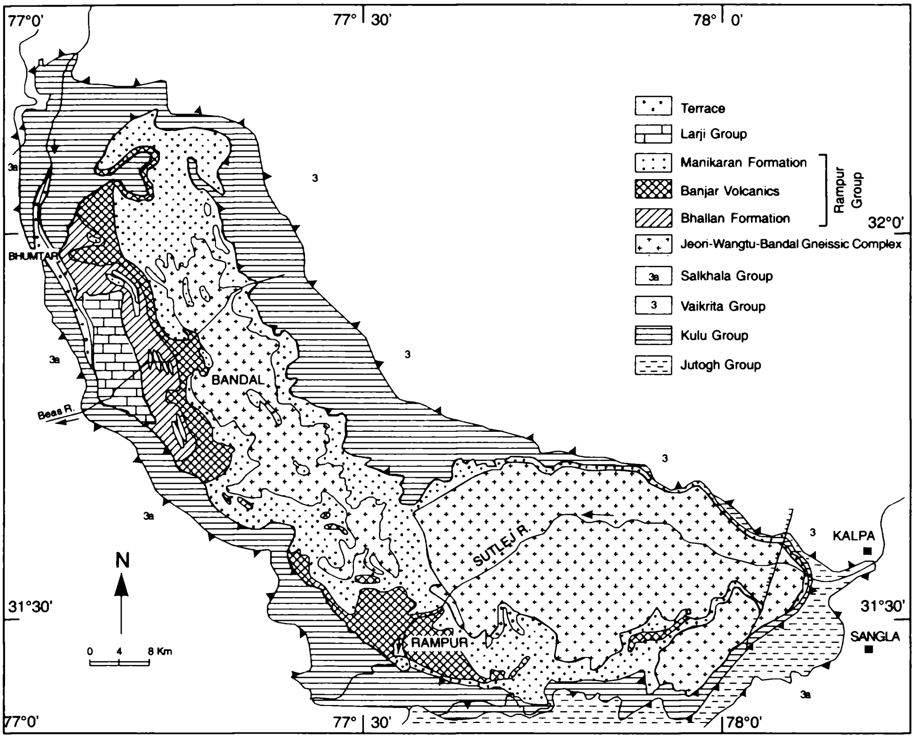
77°0'
77° 30'
78° 0'
Terrace
Larji Group
Manikaran Formation
Banjar Volcanics
Bhallan Formation
Rampur Group
32°0'
Jeori-Wangtu-Bandal Gneissic Complex
3a Salkhala Group
3 Vaikrita Group
Kulu Group
Jutogh Group
BHUMTAR
BANDAL
Beas R.
SUTLEJ R.
RAMPUR
KALPA
SANGLA
31°30'
N
0 4 8 Km
3
3a

**Fig.4H-2.** Geological map of Larji-Rampur Window Zone (Srikantia and Bhargava, 1998, p.48).

Volcanics) is essentially made of amygdular metabasalt interbedded with quartzite and phyllite; the topmost unit (Manikaran Fm.) consists mainly of quartz arenite with local metabasalts. The equivalent sequences are known by the local names of Berinag, Bhimtal and Kishtawar Groups. Rampur Group is overlain by Larji Group, which also is divided into three formations, essentially comprising quartz arenite, phyllite, conglomerate, stromatolitic dolomite and limestone.

The *Shali window* exposes Sundernagar Group with Mandi Volcanics and Shali Group. Sundernagar Group is composed of quartz arenite with interbeds of slate and phyllite. Mandi Volcanics are contemporaneous flows of tholeiitic basalt and andesite, divisible into massive, schistose and amygdaloidal types. The overlying Shali Group consists of shale and siltstone with beds of salt and marl, locally called as *lokhan*. The lokhan is either an *in situ* weathering product or a tuffaceous material. The overlying units are mainly quartz arenite, shale, siltstone, dolomite and limestone (including Tunda Pathar Limestone of Kalka). Dykes of dolerite and diorite intrude the Shali Group.

In the *Deoban window*, the succession consists of the lower Dharagarh Group and the upper Deoban Group. Dharagarh Group (old 'Chakratha Series') consists essentially of quartz arenite, amygdular to massive metabasalt and minor amounts of argillite and limestone. The limestone is at places pelletal, and grades into calc-arenite showing algal structures. The limestone in the upper portions of the sequence is marmorised (i.e., converted into marble) and is interbedded with argillite. The overlying Deoban Group is divisible into three formations: the lower shale-arenite unit, followed by the middle stromatolitic limestone, dolomite (old Deoban Limestone) and shale, intercalated with sandstone, siltstone, conglomerate and shale. The upper unit consists of oolitic and stromatolitic limestone, shale and sporadic arenite. Basic dykes and sills intrude the Deoban Group.

In *Uttarakhand Himalaya*, the equivalent rocks of Second Cycle are described in literature under various names, viz. Garhwal Group (Tejam, Pithoragarh, Rautgara or Damantha Groups, or Naraul, Berinag and Bhowali Sequences), which are locally divided into several formations. In *Nepal Himalaya*, the undivided succession of Dailekh / Jaljala Group, Kathmandu Group and Pokhara Group contains parts of the Second Cycle that are yet to be separated individually. In the *Sikkim-Darjeeling Himalaya*, this cycle is called Daling Group represented by slate and phyllite associated with quartzite. Intercalations of calcareous sediments and basic rocks are noticed. Sulphide mineralisation is recorded at places. In *Bhutan Himalaya*, the equivalents are described under Jaishudanda Formation and part of Shumar Group. In *Arunachal Himalaya*, the Second Cycle is represented by Bomdila Group, which is divided into three formations that are called by different names by different authors. The lower unit (Khetabari Fm.) consists of quartzite, garnet-mica schist, acid tuff, graphitic phyllite, tremolite marble, calc-silicate rock and para-amphibolite. The middle unit (Tenga Fm.) is marked by quartzite-basic lava alternations, with interbeds of phyllite and carbonate. Some workers regard the Tenga Formation as the lowest unit. The upper unit (Chilliepam Fm. / Dedza Fm.) represents an interbedded sequence of phyllite, quartzite, and stromatolitic dolomite/limestone. Some authors include Dirang Formation as the uppermost unit that encompasses both Khetabari and Potin Formations of other authors. Bomdila Group is intruded by meta-peridotite, amphibolite, granitic gneiss (Bomdila gneiss) and the tourmaline nodule bearing granite.

### Third Cycle

The next sedimentary sequence (Third Cycle) consists of basal conglomerate followed by arenaceous and argillaceous sediments, with minor bands of stromatolitic carbonates. The cycle ends essentially with a thick sequence of quartzite and quartz pebble conglomerate (QPC) indicating a gradual regressive phase. A characteristic feature of this sequence is the presence of evaporites, mainly as gypsum accumulations. Penecontemporaneous

**Table 4H-4.** Composite lithostratigraphy of the Third Cycle

| | |
|---|---|
| Jaunsar and Shimla Groups | Quartz arenite, quartz wacke, slate and rare conglomerate<br>Quartz arenite interbedded with slate and rare metabasalt<br>Shale-siltstone alternations with algal limestone<br>Limestone, shale, quartz arenite and boulder bed |

volcanism, which was characteristic of the Second Cycle, is absent in this sequence. The generalized succession of rocks of this cycle from Himachal and Uttarakhand is given in Table 4H-4.

### *Higher Himalaya*

In *Kashmir Himalaya*, the Third Cycle is represented by Salkhala Group in the nappe of the same name, where it is divided into the lower Hazara Slate and the upper Tanawal Formation. The succession starts with a basal conglomerate, followed by phyllite and quartzite interbedded with limestone and gypsum (Hazara Slate). Tanawal Formation is essentially a quartzite with associated phyllite and metabasic rocks. The Salkhala Group was earlier correlated with Vaikrita Group in the Central Crystallines, but the presence of gypsum beds and generally low-grade metamorphism favours correlation with the Third Cycle. The Salkhala Group in *Himachal Pradesh* is divided into two formations. The lower unit (Bhalai Formation) consists of phyllite, garnet-mica schist, micaceous quartzite and psammitic gneiss with rare bands of marble. The upper unit (Chamba Formation) comprises metagreywacke, slate, carbonaceous slate and subordinate quartzite. A linear belt of concordant granitoids of Neoproterozoic-Early Palaeozoic age (450-550 Ma), known as Dalhousie, Dhauladhar, Mandi and Karsog granites, intrudes the Salkhala Group as part of a large nappe. The overlying Kulu Group consists of three formations encompassing diverse lithotypes such as graphitic schist, garnet-mica schist, talc schist, limestone, banded gneiss and migmatite, as well as quartzite and phyllite. Kulu Group is known as Haimanta Group in Uttarakhand. Jutogh Group forms the highest allochthon in Himachal Pradesh and is distinguished from the other sedimentary sequences by its lithostratigraphy. Jutogh Group is divided into eleven formations with its base delimited by Jutogh Thrust. The lithological association includes carbonaceous phyllite, limestone, rare dolomite, ripple-marked and cross-bedded quartzite, garnet-mica schist, paragneiss and local amphibolite. The sequence is intruded by numerous dolerite dykes and sills. Chaur gneiss, which consists of streaky, porphyroblastic and augen gneisses, as well as Kainchwa and Pabar gneisses, intrude the sequence, whereas there is a view that the gneisses may constitute the basement.

### *Lesser Himalaya*

In the Lesser Himalaya of *Himachal Pradesh* and the adjacent *Uttarakhand*, a younger pile of metasediments called the Simla and Jaunsar Groups overlie the carbonate sequence of Shali and Deoban Groups unconformably, and at places with a tectonic contact. The sequence extends in the west up to Kashmir as Ramban, Gamir and Baila Formations, and further west of the Kashmir syntaxis as Hazara Group. The Simla Group is divided into four formations with a conglomerate and quartzite at the base followed by a succession of shale, siltstone, limestone, dolomite and greywacke, and ending with conglomerate and arkosic sandstone. Simla Group is free from volcanics, but dolerite dykes are common. The overlying Jaunsar Group is developed as an autochthonous unit in the Deoban belt, but as a nappe in Uttarakhand. Jaunsar Group is divided into three formations consisting of quartzite with impersistent lenticular conglomerate, limestone, shale, siltstone, greywacke with minor lava flows and finally by a series of quartzites interbedded with phyllite. Kharsali gneiss occurs either as intrusive or as a tectonic slice of the basement within Jaunsar Group. 'Chail Series', interpreted earlier as a thrust sheet above the Jaunsar Group, is now known to be part of the succession of Jaunsar Group.

The equivalents of the Third Cycle are Lakharpata Subgroup and lower Nawakot Group in Nepal and Shumar Formation in Bhutan. Shumar Formation comprises an alternating sequence of quartzite and mica schist with impersistent bands of carbonate and lenses of gypsum. The best exposures are seen in Saumar and Kuru Chu where the sequence has been divided into a few separate members. Several concordant bodies of mylonitised granite gneiss are seen within the mica schist. Shumar Formation has been correlated with the Garubathan Formation and part of Buxa Group of Sikkim-Darjeeling area.

## Fourth Cycle

The Third Cycle is separated from the Fourth Cycle by a major diamictite horizon popularly known as Blaini Formation (or informally as Blaini Boulder Bed) in Himachal Pradesh and Uttarakhand. The Fourth Cycle occurs in two parallel and apparently independent belts, namely, the Outer Krol Belt above the Simla Group and the Inner Krol Belt over the Jaunsar Group. The Terminal Precambrian to Eocambrian Tal Group is exposed only in the Inner Krol Belt. The generalized stratigraphy of the Fourth Cycle is given in Table 4H-5.

Blaini Group is divisible into four formations in the Inner and Outer Krol belts. The basal unit is a boulder bed with clasts of quartzite, shale, siltstone, limestone, chert and vein quartz, embedded in an argillaceous matrix. The origin of this boulder bed is controversial. It is described as a submarine slump deposit

**Table 4H-5.** Generalised Stratigraphy of Fourth Cycle

| | | |
|---|---|---|
| Krol Group | | Calcareous sandstone, quartz arenite, dolomite, limestone, phosphatic chert, black shale, rare conglomerate |
| | | Shale, dolomite, gypsum lenses, oolitic limestone |
| | Krol Sandstone | Quartz arenite with fragments of phosphatic shale |
| | Infra Krol | Black shale, slate, slaty quartzite |
| Blaini Group | | Shale and interbedded dolomitic limestone |
| | | Boulder bed with clasts of earlier sediments in a variable matrix |
| | | Shale, slate, quartzite, varved argillite and rare conglomerate |
| | | Boulder bed with assorted clasts and variable matrix |

of turbidite origin, or a glacio-marine deposit that indicates the incidence of Neoproterozoic glaciation in the Lesser Himalaya. The Blaini boulder bed is succeeded by shale, slate, quartzite and dolomitic limestone with another intervening boulder bed.

The Infra-Krol, which was earlier given a separate stratigraphic status, is now found to be the basal part of the Krol Group, and consists of a dominantly argillaceous component of the shale, slate and phyllite with minor quartzite bands. There is no break in deposition between Infra-Krol and Krol sequences. The Infra-Krol is overlain by Krol Sandstone in the Outer Krol Belt. The Krol Sandstone is not developed in the Inner Krol Belt and consists of quartz arenite containing fragments of phosphatic shale. The overlying unit in both the Krol belts (Inner and Outer) comprises of alternations of shale and thin dolomite and limestone. Lenticular gypsum beds are associated with the limestones in the Inner Krol belt. Limestone, shale, arenite and rare conglomerate constitute the top portion of Outer Krol belt, whereas dolomite, limestone, phosphatic chert and pockets of gypsum and barite in calcareous shale are found at the top of the Inner Krol belt. Dolerite dykes and sills intrude Krol Group at several places. Krol Group yields algae, acritarchs, stromatolites and oncolites referred to Neoproterozoic. The limestone from the top of Krol Group is reported to contain Ediacaran fauna, which is a distinctive assemblage of soft-bodied metazoans (mostly coelentrates), metaphytic algae and trace fossils. These taxa are comparable with the Ediacaran assemblage of Australia, Eurasia and Canada, which suggest that Krol Group is Terminal Proterozoic. The top unit of shale of Krol Group is dated by Rb-Sr WR method to be 626±13 Ma. The overlying Tal Group consists of three formations, essentially made of shale, siltstone, sandstone, limestone, chert and phosphorite. The Tal Group contains abundant microshelly fauna of Lower Cambrian age. This is followed by a period of regression and non-deposition until Paleogene.

The equivalent of the Fourth Cycle in the Lesser Himalaya of Arunachal Pradesh is the Dedza (Chilliepam) Formation at the top of Bomdila Group and consists of grey phyllite, limestone/dolomite and minor quartzite. The equivalent formation in Nepal Himalaya forms part of Nawakot Group.

## STRUCTURE

The six longitudinal zones of the Himalaya and the thrusts/faults that delineate them, described in the introduction, are important tectonic entities in the Himalayan orogen. Of these, the Higher Himalaya bounded by the Main Central Thrust in the south is the most significant fold-thrust belt where the Proterozoic basement rocks are involved in the Tertiary Himalayan orogeny. The Frontal Fold Belt consisting of Subathu, Murree and Siwalik sediments resting on Proterozoic basement, is separated from the Indo-Gangetic alluvium by the Himalayan Frontal Thrust. This frontal fold belt in the Outer Himalaya is separated from the next higher zone of Lesser Himalaya by the Main Boundary Thrust (MBT) in most areas and by the Murree Thrust in Jammu and Krol Thrust in Himachal Pradesh. The Geological Survey of India recognized the fault between the Siwalik and Murree as Main Boundary Fault (MBF)-II. Due to mutual fold-fault relations between the different lithological associations, the frontal fold belt is regarded as *schuppen* zone. The fold patterns in the Murree and Siwalik zones are marked by open low plunging folds, with axial trace parallel to the Himalayan trend. The intensity of folds increases close to the boundary faults as the result of which the limbs become inverted and reverse faults are formed. The alluvial zones show broad homoclinal northerly dips. The zones are shown below in Table 4H-6.

The Lesser Himalaya is bound by the MBT in the south and MCT in the north. Opinion prevails that MCT is not a single plane but consists of two parallel thrusts MCT-I and MCT-II. Further, MCT is interpreted differently in different sectors of the Himalaya. One group visualizes it as linking up with the Jutogh and Panjal thrusts. Others include Vaikrita Thrust under MCT. The two Almora Thrusts are the other important faults. The Central Crystallines of Higher Himalaya occurring to the north of MCT is separated from the Tethyan Himalaya by Trans-Himadri Thrust, Martoli Fault or Zanskar Fault, that is known by different names elsewhere. There are many other tectonic planes parallel to the Himalayan trend between MCT and Almora Thrust. There are also numerous cross faults trending NW-SE.

A comprehensive picture of folding in Himalaya is yet to emerge because of insufficient data. Three phases of folding ($F_1$ to $F_3$) are recorded from Proterozoic sediments. $F_1$ folds are tight to isoclinal, $F_2$ folds are moderately tight to open asymmetric folds and $F_3$ are moderately tight folds. The relation

**Table 4H-6.** Simplified Tabular Cross Section of the Himalaya

- **Main Karakorum Thrust**
  - Shyok Suture Zone
  - Karakorum-Ladakh Zone
- **Main Mantle Thrust**
  - Indus-Tsangpo Suture
  - Tethyan Himalaya
- **Trans-Himadri Thrust**, Martoli Fault, Zanskar Fault
  - Higher Himalaya
- **Main Central Thrust** (MCT), Vaikrita Thrust
  - Lesser Himalaya
- **Murree Thrust**, Krol Thrust, MBT-I
  - Murree Formation
- **Main Boundary Thrust**, MBT-II
  - Siwalik Group
- **Himalayan Frontal Thrust**
  - Indo-Gangetic Alluvium

of these folding phases with main Himalayan deformation that produced faults, thrusts and ductile shear zones is not clearly understood. While some workers relate $F_1$ to regional faults, thrusts and ductile shear zones, others relate $F_2$ and $F_3$ to the emplacement of thrust sheets, but these views are debatable. Thrust deformation is accompanied by large amounts of extensional strains. A series of open asymmetric to overturned folds ($F_4$) having trends parallel to the arcuate Himalayan Mountains with northerly dips, have affected the sequences from Proterozoic to Eocene. These folds are regarded as transverse structures that are controlled by the structures of the Indian shield during the evolution of the thrust system. The $F_4$ folding phase is correlatable with the main Himalayan orogeny. The youngest set of broad open folds ($F_5$) with northerly plunge has affected all the earlier structures. $F_4$ and $F_5$ may represent conjugate folds.

The Indus-Tsangpo Suture Zone or the Main Mantle Thrust shows $F_1$ folds that are tight to isoclinal with axes trending NW-SE to WNW-ESE and having moderate plunge on either side. Cross folds and thrusts are seen locally. The Shyok Suture Zone and the Main Karakoram Thrust are considered older than the Indus Suture Zone. The collision of India with Asia was considered diachronous, resulting in oblique convergence beginning in western Himalaya at 65-55 Ma and terminating in the east at 50-45 Ma, with the counterclockwise rotation of India (Fig.4H-3).

The Trans-Himalayan zone consists of calc alkaline volcanics, Kohistan

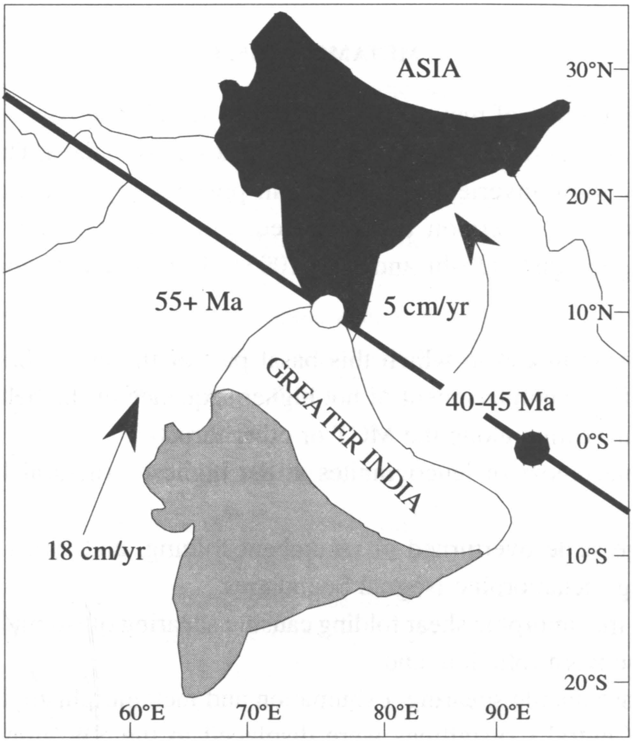

**Fig.4H-3.** Counterclockwise rotation of India (modified after Tapponnier et al. 1986).

and Ladakh batholiths (including numerous gneiss domes), Chilas igneous complex, Gandise magmatic belt of Tibet and Indus Formation in the western sector. The Indus Formation is interpreted either as Cretaceous arc-trench gap sediments or Tertiary continental deposits overlying the batholith. Similarly, in the eastern sector, the Lohit granodiorite and Tidding Formation are separated from the Tethyan Himalaya by the Tidding Suture of post-Lower Eocene and pre-Middle Miocene age. In the northwest, the Karakoram batholith associated with Pangong Tso Formation is separated from the Tethyan Himalayan belt by the Shyok Suture Zone that is reworked along the Main Karakorum Thrust. The Pangong Tso Formation is involved in three phases of deformation, with isoclinal $F_1$ folds, open folds of $F_2$ coaxial with $F_{1,}$ and open $F_3$ folds associated with parallel faults.

There are many syntaxial bends in the Himalaya from west to east such as Indus, Hazara-Kashmir, Nanga Parbat-Haramosh, Teesta, Siang and Namche Barwa. These are formed by the wrapping of the Himalayan structures around the promontories of basement gneisses of Indian shield, which culminated in the slides developing around the syntaxial bends. Lateral arches of thrust surfaces in the form of culminations develop recesses in the MCT in eastern Himalaya.

## METAMORPHISM

Extensive tracts of metamorphic rocks are seen in the Higher Himalayan Crystallines and crystalline thrust sheets in the Lesser Himalaya. The crystalline thrust sheets show inverted metamorphism prominently. Various causes of this metamorphic inversion are proposed, but consensus has eluded the Himalayan geologists (Joshi and Rai, 2003). The different models are the following:

(i) Hot-iron model in which this basal part of the crystallines is heated due to the emplacement of hot higher sequence of the belt,
(ii) Shear heating along the MCT or other thrusts,
(iii) Emplacement of leucogranites at the highest structural levels in the belt,
(iv) Large scale overturned or recumbent folding, and thrust imbrication along metamorphic isograd boundaries,
(v) Syn-metamorphic shear folding causing shearing of isograds discordant to the main foliation, and
(vi) Intense ductile shearing, exhumation and metamorphism during which the Central Crystallines were displaced to the SW along a C-shear foliation in a major shear zone causing inverted metamorphism. In this model, the MCT postdates these metamorphic events.

The autochthonous to para-autochthonous volcano-sedimentary sequences of Lesser Himalaya, on the other hand, are unmetamorphosed to weakly metamorphosed. The suture zones, batholiths and associated volcano-sedimentary successions to the north of Indus-Tsangpo suture zone show the impress of the main Himalayan metamorphism. Eclogites and garnet granulites of Nanga Parbat-Haramosh massif are formed at 650±50° C and 10±3 kb. Locally the metamorphic pressures go up to 16±2 kb and the highest pressures recorded so far are 20±2 kb. The high-pressure metamorphism is assigned to $M_1$ event of Middle Eocene to Early Oligocene (30-40 Ma) age, followed by decompression during $M_2$ event (750° C at 4-8 kb) during Miocene (13-22 Ma). Further east in Garhwal and Nepal, the Tertiary metamorphism was in amphibolite facies (*see* Guillot et al. 1999).

Regional metamorphism of intermediate pressure type (Barrovian followed by Buchan type) is noted in the Central Crystallines and the crystalline thrust sheets. The highest grades of metamorphism (~700° C/7.5 kb) are invariably associated with generation of migmatites and anatectic granites by partial melting of the crustal rocks. The 1865 Ma age of Almora Nappe indicates that the upper amphibolite facies metamorphism is of Palaeoproterozoic age (Joshi and Tiwari, 2004). The thrust sheets of Lesser Himalaya occur as thrust-bound asymmetrical synforms in tectonic contact with unmetamorphosed to weakly metamorphosed sequences. In Uttarakhand, the greenschist facies assemblages in pelites are muscovite, chlorite, quartz, stilpnomelane and biotite. In amphibolite facies, the assemblages are biotite, garnet, muscovite, plagioclase, kyanite, staurolite and sillimanite. This metamorphism called $M_2$ has outlasted deformation as seen from mineral textures. The $M_2$ metamorphism ranges in temperature from 580 to 770°C and pressure from 5 to 7.7 kb. The nature of $M_1$ metamorphism, probably of Proterozoic age, as seen in the basement gneisses is not clearly understood, as it is superposed by the Tertiary high-grade metamorphism and widespread anatexis.

## MAGMATISM

The basement gneisses of Central Crystallines of Higher Himalaya and the gneisses of crystalline thrusts in Lesser Himalaya yield ages varying from 2200 to 1800 Ma (Palaeoproterozoic) that marks First Cycle in the Himalaya. The indication of still older (Neoarchaean), inherited components, deduced from zircon U-Pb ages, is seen in the dates of 2500-2700 Ma. The Palaeoproterozoic event is succeeded by the next episodes of granitic activity about 1500-1600 Ma and 1100-1200 Ma. These events mark the culmination of Mesoproterozoic sedimentary cycles (Second and Third Cycles). The next important event is the emplacement of Pan-African granites (Neoproterozoic to Early Palaeozoic) that are widespread throughout the Himalayan succession. These granites range in age from 450-550 Ma and cut across all earlier deformation features in the associated rocks. This event marks the culmination of Precambrian sedimentary cycles in Himalaya, represented by the widespread Neoproterozoic glaciation (Blaini) ending with the deposition of Krol Group. Phanerozoic sedimentation follows this major Precambrian event. Extensive development of leucogranites (12-32 Ma, but rarely 4 and 1 Ma) is seen during the main Himalayan orogeny. These granites are believed to be generated by the anatexis of Proterozoic pelitic gneisses of the Himalaya. The metamorphism related to this latest event is of low-pressure type.

**Table 4H-7.** Chronology of Precambrian Events in the Himalaya

| | | |
|---|---|---|
| Cycle IV | Krol<br>Blaini | 450-550 Ma |
| Cycle III<br>(and partly II) | Simla and Jaunsar Groups<br>Carbonate belts of Shali, Deoban etc. | ~1000 Ma<br>1100-1200 Ma |
| Cycle II | Quartzite – metabasalt association of Rampur/Sundernagar Group and allied groups | 1500- 1600 Ma |
| Cycle I | Basement Gneisses | 2200-1800 Ma |

The main Precambrian events in the Himalayan belt are given in (Table 4H-7).

## TECTONIC EVOLUTION OF THE HIMALAYA

The northern edge of the Indian shield is marked by the Proterozoic 'Purana' sedimentary basins overlying the crystalline basement with a profound unconformity. The basement consists of the Mewar and Bhilwara gneisses together with the Aravalli-Delhi orogen in Rajasthan (Aravalli craton), Bundelkhand granite with older supracrustals (Bundelkhand craton), and Chhotanagpur Gneiss (part of Satpura mobile belt) in eastern India and Shillong Plateau of northeast India. This basement complex has been thrust up and folded in the Central Crystallines of Vaikrita Group and its equivalents in the metamorphic core of the Himalaya. The basement is also exposed as detached thrust belts forming several tectonic windows in the Lesser Himalaya amidst unmetamorphosed to low-grade Himalayan succession. The regional spread of the ages of this basement is from 2200 to 1800 Ma (Palaeoproterozoic) and no major Archaean component is recorded so far, except as vestiges of protolith ages. This event probably represented the oldest lithotectonic cycle (Cycle I) in the Himalaya. The overlying sedimentary successions of Himalaya correspond to the 'Purana' platform basins of the Indian shield.

The sedimentation in the Second cycle (Cycle II) commenced under unstable platform conditions, associated with intra-continental rifting and basic volcanism represented by the quartzite-metabasalt succession of Rampur, Sundergarh and Dharagad Groups in Himachal Pradesh. This succession is dated around 1500-1600 Ma. This second cycle of sedimentation with associated magmatism has probably affected the basement gneisses that also show similar ages as this cycle. The third cycle (Cycle-III) of sedimentation is characterized by extensive development of carbonate facies with associated gypsum accumulations, and capped by thick shale sequences. There are no volcanics associated with the cycle. Stromatolites become prolific in the limestones and dolomites. This cycle ends with an arenaceous sequence associated with quartz pebble conglomerate indicating a regressive phase and uplift of the provenance. The age of this cycle is approximately of 1000-1200 Ma. The associated gneisses and younger granites in the tectonic windows of Lesser Himalaya and within Higher Himalaya also indicate similar ages.

The last Precambrian cycle (Cycle IV) of the Himalaya is separated by a major unconformity represented by a diamictite sequence. This sequence has also major carbonate, chert and phosphorite horizons associated with shales and arenites. The Precambrian-Cambrian boundary lies within this cycle in the basal part of Tal Formation. A rapid evolution of life is evidenced by the abundant fossils of algae, acritarchs and Ediacaran fauna. A large-scale regression of the sea connected with a major uplift in Pan-African times (450-550 Ma) occurred at the end of the cycle. Extensive plutonic activity marked by intrusion of abundant granitoids in the Himalaya during the Pan-African event is important.

Phanerozoic evolution of the Himalaya commences with the northward drift of India from Antarctica over a distance of 7000 km commencing with the break up of Gondwana supercontinent during Late Jurassic-Early Cretaceous about 150 Ma ago. Madagascar and Seychelles separated en route during the long journey, followed by the outpouring of plume-generated Rajmahal Traps (115 Ma) and Deccan Traps (Parh Group in Pakistan) at 65 Ma. The Indian continent collided with Asia first in the west at 65-55 Ma along the Shyok suture with the development of Karakoram batholith further north (Fig.4H-4a). The next stage of collision took place at 50-45 Ma along the Indus-Tsangpo suture with the evolution of Trans-Himalayan batholith to the north (Fig.4H-4b). The Tidding suture in the east separated the Arunachal Himalaya from the Arakan Yoma Belt of Myanmar (see Fig.4H-1a). The eastward suturing took place during the counter-clock rotation of India. This model of tectonic evolution is supported by geophysical data, which show a crustal thickness of 40 km in the shield and 80 km below Tibetan Plateau.

The Himalayan orogen is characterized both by thick-skinned (basement reactivation of crystalline sequences) and by thin-skinned tectonics of the fold-and-thrust belt (Gehrels et al. 2003). All the Himalayan faults are probably related to a mid-crustal décollement. The sequence of thrusting is seen to young from north to south towards the Foreland Siwalik basin. The Siwalik molasse sediments are faulted and folded. The Outer Himalaya is overthrust

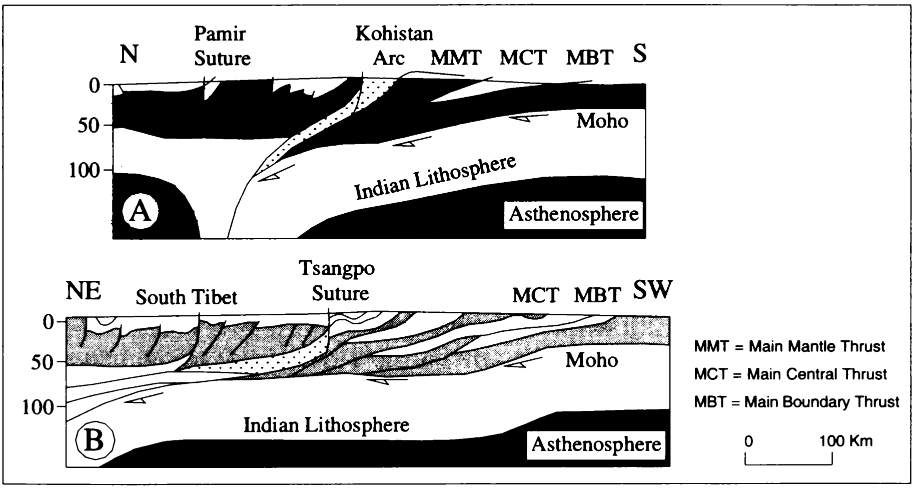
N
Pamir Suture
Kohistan Arc
MMT
MCT
MBT
S
0
50
100
Moho
Indian Lithosphere
Asthenosphere
A
NE
South Tibet
Tsangpo Suture
MCT
MBT
SW
0
50
100
Moho
Indian Lithosphere
Asthenosphere
B
MMT = Main Mantle Thrust
MCT = Main Central Thrust
MBT = Main Boundary Thrust
0
100 Km

**Fig.4H-4.** (**A**) Cross-section across Western Himalaya. (**B**) Cross-section across Eastern Himalaya (after Guillot et al. 1999).

by the Lesser Himalaya and the Indo-Gangetic alluvium by the Sub-Himalayan overthrust called the Himalayan Frontal Thrust. The zones of thin-skinned tectonics are related to the frequent seismicity in the Himalaya.

Recently, channel flow models involving the movement of a low viscosity crustal layer in response to topographic loading are invoked and debated upon (Harris, 2007).

The fascinating evolutionary history of Himalaya from Precambrian to Phanerozoic is summarised in the following table (Table 4H-8).

**Table 4H-8.** Major Geological Events in the Himalaya (after Valdiya, 1998)

| ERA | AGE (m.y) | MAJOR EVENTS |
|---|---|---|
| Quaternary | 0.011 | Rapid uplift along active faults |
| Tertiary | 1.6 | Tremendous uplift of Himalaya; Deformation of Siwalik and formation of Himalayan Frontal Fault; Evolution of Indo-Gangetic basin (~1.7-1.5 m.y.) |
|  | 5.6 | Formation of Main Boundary Thrust; Emergence of Siwalik; Beginning of Indo-Gangetic foreland basin (~2.5-2.0 m.y.) |
|  | 23 | Formation of Main Central Thrust and Trans-Himadri Fault; Widespread emplacement of granite; Evolution of Himadri; Uprooting and overthrusting of Lesser Himalayan nappes; Formation of Siwalik foreland basin (~2.5 to 20 m.y.) |
|  | 36.5 |  |
|  | 53 | Ridging up of Asia-India junction; Establishement of drainages of Sindhu, Ganga and Brahmaputra systems |
|  | 65 | Collision and welding of India with Asia; Emplacement and squeezing out of sea floor rocks; Formation of elongate basins north and south of emerging Himalayan province (~65-55 m.y.) |
| Mesozoic | 135 | Formation of oceanic trench; Development of volcanic island arc in front of Asian landmass |
| Palaeozoic | 250 |  |
|  | 290 | Hercynian diastrophism<br>Rifting of crust and volcanism in southern belt; Incursion of sea along the rift valley; Widespread glaciation; Interruption of sedimentation in Tethys domain (~310-280 m.y.) |
|  | 355 |  |
|  | 410 |  |
|  | 438 |  |
|  | 510 | Pan-African diastrophism<br>Cessation of sedimentation in Lesser Himalayan domain; Widespread emplacement of granite; Interruption of sedimentation in Tethys domain (~540-470 m.y.) |
| Proterozoic (Purāna) | 570 |  |
|  | 650 |  |
|  | 1000 |  |
|  | 2050 | Start of sedimentation with disturbed tectonic condition; Basic volcanism in some centres |

#  5

# Proterozoic Sedimentary Basins

## INTRODUCTION

A number of nearly flat-lying, virtually unmetamorphosed and partly deformed Proterozoic cratonic basins forms a significant part of the Precambrian shield of India (Fig 5.1). These basins predominantly contain orthoquartzite-shale-carbonate suites varying in thickness from 100 to 10,000 m and deposited episodically, with frequent breaks in sedimentation, over a time span of about 600 m.y. These are called "Purana" basins in Indian stratigraphy after Holland (1907), like the Riphean of Russia with which these basins have often been compared because of their great similarities. The Hindi word 'Purana' means 'ancient,' and is "necessarily a somewhat vague though most convenient term" (Pascoe, 1950, p.38) to refer to most of the sub-horizontal Precambrian sedimentary sequences deposited over the crystalline basement of gneisses, granites and schists. The profound unconformity between the crystalline basement and the Purana basins, seen in the field as a sharp, erosional, angular unconformity or non-conformity, marked invariably by basal conglomerates, was called in early literature as the Great Eparchaean Unconformity. Recent advances in the Precambrian geology have rendered such terminology as 'Eparchaean Unconformity' and 'Purana' basins obsolete *in the global context* for the following reasons: (i) The International Subcommission on Precambrian Stratigraphy has fixed the Archaean-Proterozoic boundary as a geochronological datum at 2500 Ma without reference to any particular stratotype, and (ii) the crystalline basement in India is not necessarily Archaean everywhere, as seen in some Proterozoic supracrustal belts unconformably underlying the sub-horizontal basins (e.g. Kotri-Dongargarh belt underlying Chhattisgarh basin). 'Purana' is however a useful omnibus term *in the Indian context* to refer to a group of sub-horizontal Proterozoic sedimentary sequences of the Peninsular Shield.

The Purana basins are mainly intra-continental basins, described commonly as cratonic or epicratonic basins. They are mostly situated close to

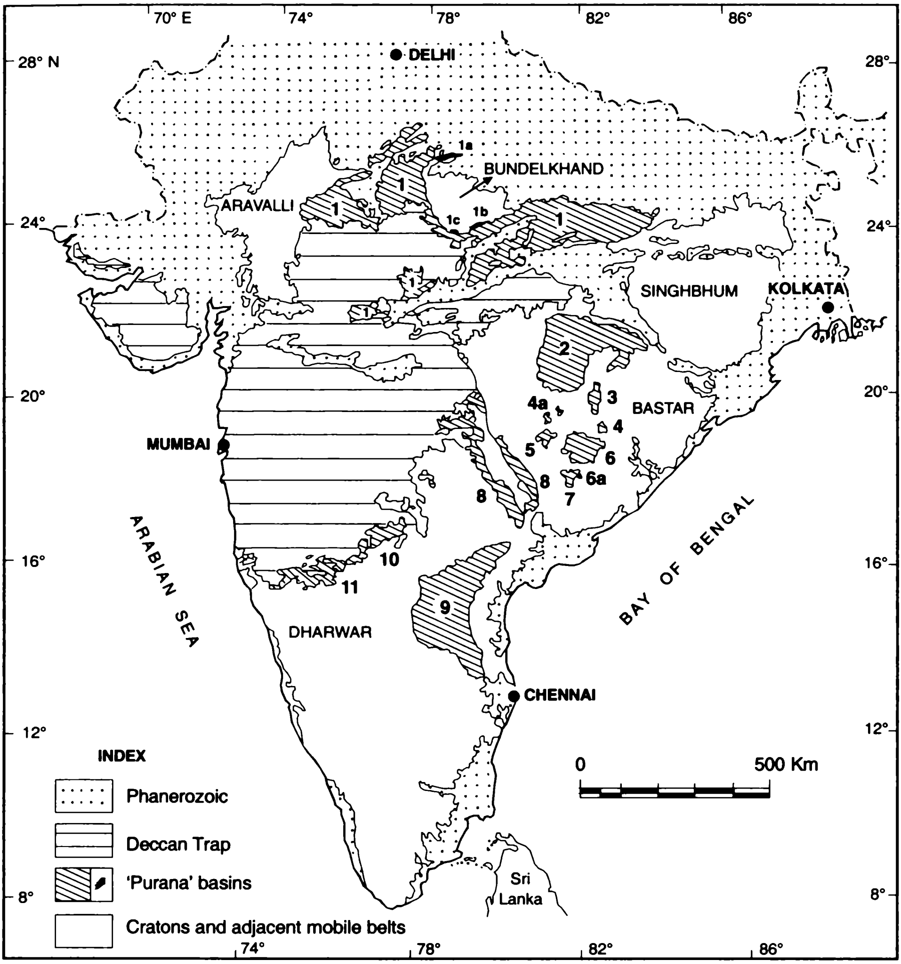
70° E
74°
78°
82°
86°
28° N
24°
20°
16°
12°
8°
DELHI
1a
BUNDELKHAND
ARAVALLI
1
1b
1c
SINGHBHUM
KOLKATA
2
3
4a
4
BASTAR
MUMBAI
5
6
6a
7
8
ARABIAN SEA
BAY OF BENGAL
10
11
9
DHARWAR
CHENNAI
0
500 Km
INDEX
Phanerozoic
Deccan Trap
'Purana' basins
Cratons and adjacent mobile belts
Sri Lanka

**Fig.5.1.** Purana basins of Peninsular India within different cratons (after Kale, 1991). **1** -Vindhyan, **1a** - Gwalior, **1b** - Bijawar & **1c** - Sonrai basins, **2** - Chhattisgarh basin, **3** - Khariar basin, **4** - Ampani basin, **4a** - Keskal and Singanpur outliers. **5**- Abujhmar basin, **6** - Indravati basin, **6a** - Chedrapal outlier, 7 - Sabari basin, **8** - Pranhita-Godavari basin, **9** - Cuddapah basin, **10** - Bhima basin, 11 - Kaladgi basin.

the periphery of cratons (pericratonic basin); some may be located in the cratonic interior (intra-cratonic basin like Kaladgi, Bhima), and rarely between cratons (inter-cratonic basin like the Pranhita-Godavari basin lying between Dharwar and Bastar cratons). They are also described as platform basins (*see* Sleep et al. 1980). Their sediments have sampled the Archaean crust and therefore are witness to the story of early crustal evolution. Their study is useful for global comparison with similar basins in Canada, Australia and Africa that will help to understand the Earth's Proterozoic crustal development and the land-sea interactions during that period. Importantly, these basins unveil the prelude to the Cambrian explosion of life.

The Purana basins are of diverse shapes and sizes and occupy an aggregate area of ~3,50,000 km$^2$, nearly half of which is presently exposed, and the remaining either concealed under younger cover or lost by denudation. They occupy nearly 20% of the area of the Precambrian of Peninsular India (Kale, 1991) and contain thick unconformity-bounded transgressive and regressive sequences deposited dominantly in shallow water (15-20 m water depth). The common depositional environments are fluvial to shallow marine (deltaic, beach, littoral, lagoonal, tidal flat etc.) grading into shelf-slope-basin setting. Aeolean and evaporitic (sabkha) environments are locally developed. Glacial and glacio-fluvial successions, recorded from other comparable global basins, are not yet *established* on all-India basis from the Purana basins. Sedimentological studies have shown that the surrounding basement of granites and gneisses constitutes the main provenance for the Purana sediments. Purana basins are vast repositories of limestone and dolomite, and other economic minerals like bedded barytes, phosphorite, chrysotile asbestos, base metals and building stones. Contemporaneous intrusions of kimberlite and lamproite within and outside the basins, together with the sediments of the basins themselves, are a good source of diamonds and are being explored intensively in recent times. Similar intrusions of alkaline rocks and carbonatites are also potential hosts for a variety of economic minerals. The vast expanse of Purana sediments concealed under the Indo-Gangetic Alluvium at the foot of the Himalaya may offer scope for oil exploration, although no significant 'strike' has been made so far. Recent summary accounts of the 'Purana' basins are available in the 'Proceedings of the Symposium on Purana Formations of Peninsular India,' University of Sagar (1978), 'Purana Basins of Peninsular India' (Mem. Geol. Soc. India, No.6, 1987), Jayaprakash (2007) and reviews by Kale and Phansalkar (1991), Kale (1991) and Tandon et al. (1991).

The main Purana basins are Mesoproterozoic (1600-1000 Ma) in age and are spatially associated closely with Proterozoic mobile belts like the Eastern Ghats and Satpura. The Palaeoproterzoic Purana basins, on the other hand, are isolated, small sedimentary basins with near-basal volcanism, and are probably related to intra-cratonic orogens like Kotri-Dongargarh orogen (Abujhmar basin), and peripheral orogens like Mahakoshal/Hindoli belts (Bijawar and Gwalior basins) and Nellore-Khammam belt (Papaghni sub-basin of Cuddapah basin). Kolhan basin of Singhbhum craton may also be Palaeoproterozoic, but has no major volcanics in the lower part. It is also not spatially associated with any known Mesoproterozoic Purana basins. In view of these differences, Kolhan basin is described separately under Singhbhum craton. Similarly, the Neoproterozoic to Eocambrian Marwar basins in the Aravalli craton are also not included under the Purana basins. The amalgamation of the cratons of the Peninsular Shield took place, not in Archaean as generally believed (*see* Rogers, 1986), but after the cessation of intra-cratonic (Kotri-Dongargarh) and peripheral (Hindoli and Mahakoshal) orogenies in Palaeoproterozoic and paved the way for the deposition of the main Purana basins over the amalgamated cratons (*see* Ramakrishnan, 2003a).

The Proterozoic sedimentary basins are listed below (Fig.5.1) with reference to the associated cratons:

*A. Palaeoproterozoic Basins*

| | |
|---|---|
| 1. Bijawar and Sonrai basins and Harda Inlier | Bundelkhand craton |
| 2. Gwalior basin | |
| 3. Abujhmar basin | Bastar craton |
| 4. Papaghni sub-basin (Cuddapah basin) | Dharwar craton |

*B. Mesoproterozoic Basins*

| | |
|---|---|
| 1. Vindhyan basin | Bundelkhand craton |
| 2. Chhattisgarh basin | Bastar craton |
| 3. Khariar basin | |
| 4. a. Ampani basin,<br>b. Keskal, Singanpur and Chedrapal outliers | |
| 5. Indravati basin | |
| 6. Sabari (Sukma) basin | |
| 7. Pranhita-Godavari basin | Between Bastar and Dharwar cratons |
| 8. Cuddapah basin | Dharwar craton |
| 9. Kaladgi basin | |
| 10. Bhima basin | |

## PALAEOPROTEROZOIC BASINS

### Bijawar Basin

Bijawar basin (Fig.5.2) named after Bijawar town, trends ENE-WSW for about 100 km with a width of 4 to 20 km from Ken River in the east to Sonrai in the west. The basin is sandwiched between Bundelkhand granite and Vindhyan sediments. Early studies in the basin were by H.B. Medlicott in 1859, A.F. Wilson in 1873-1877, G. Mani in 1969 and S.M. Mathur in 1970. The sediments of the Bijawar Group are deposited non-conformably over the Bundelkhand granite, and with angular unconformity over the older supracrustal enclaves (BIF) at Girar. The sediments generally have low dips, but are locally folded and faulted and have an estimated thickness of <1000 m. (Pant and Banerjee, 1990; Kumar et al. 1990; Haldar and Ghosh, 2000; GSI, 2004). The stratigraphic succession of Bijawar Group modified from Kumar et al. (1990) and GSI (2004) is as follows:

| | | |
|---|---|---|
| Bijawar Group | Karri Sandstone | Gangau Subgroup |
| | Hirapur Phosphorite | |
| | Malehra Chert Breccia | Moli Subgroup |
| | Pukhra Sandstone | |
| | Dargawan Sill | |
| | Bajno Dolomite | |
| | Bhusor Basalt | |
| | Kawar Conglomerate | |

Bijawar Group commences with a basal quartz pebble conglomerate (Kawar Conglomerate), overlain by a thick pile of mafic lava (Bhusor Basalt) that was described loosely in earlier literature as Bijawar lava. Stromatolite bearing dolomitic limestone (Bajno Dolomite) is the next overlying unit. A major basic intrusion called the Dargawan Sill is emplaced within the carbonate sequence. The basic sill is succeeded by sandstone (Pukhra Sandstone) grading into chert breccia (Malehra or Pundowan Chert Breccia). The overlying unit of Hirapur Phosphorite consists of ferruginous shale and phosphatic siltstone. The youngest formation is Karri Sandstone consisting predominantly of ferruginous sandstone and shale with intraformational ferruginous conglomerate and breccia. These sediments are probably deposited in shallow water, high energy, near shore environment in a rift basin.

The mafic flows and intrusion (300 m thick) occur in three sectors of the basin, namely the Bhusor basic lava in the east, Dargawan basic sill in the centre and Kurat pillow lava in the west. Bhusor Basalt is about 90 m thick and consists of five simple flows with intervening volcanic breccia and tuff. The flows are mainly massive, but locally amygdular and pillowed, and have columnar, hackly and platy joints. The basalts are unmetamorphosed and consist of subcalcic augite, plagioclase ($An_{65-85}$), bronzite, olivine ($Fo_{65-70}$) and glass. They are essentially continental tholeiitic basalts and basaltic andesites with low P and Ti and high LILE and LREE. The basal section contains picrobasalts with quench texture. The lavas were probably derived by low degree of partial melting of a depleted mantle source, and affected by crustal contamination during ascent. The Rb-Sr age of Dargawan Sill is 1789±71 Ma and of the Kurat lava is 1691±180 Ma, which indicate a time span of 1700-1800 Ma for the Bijawar Group (*see* Haldar and Ghosh, 2000).

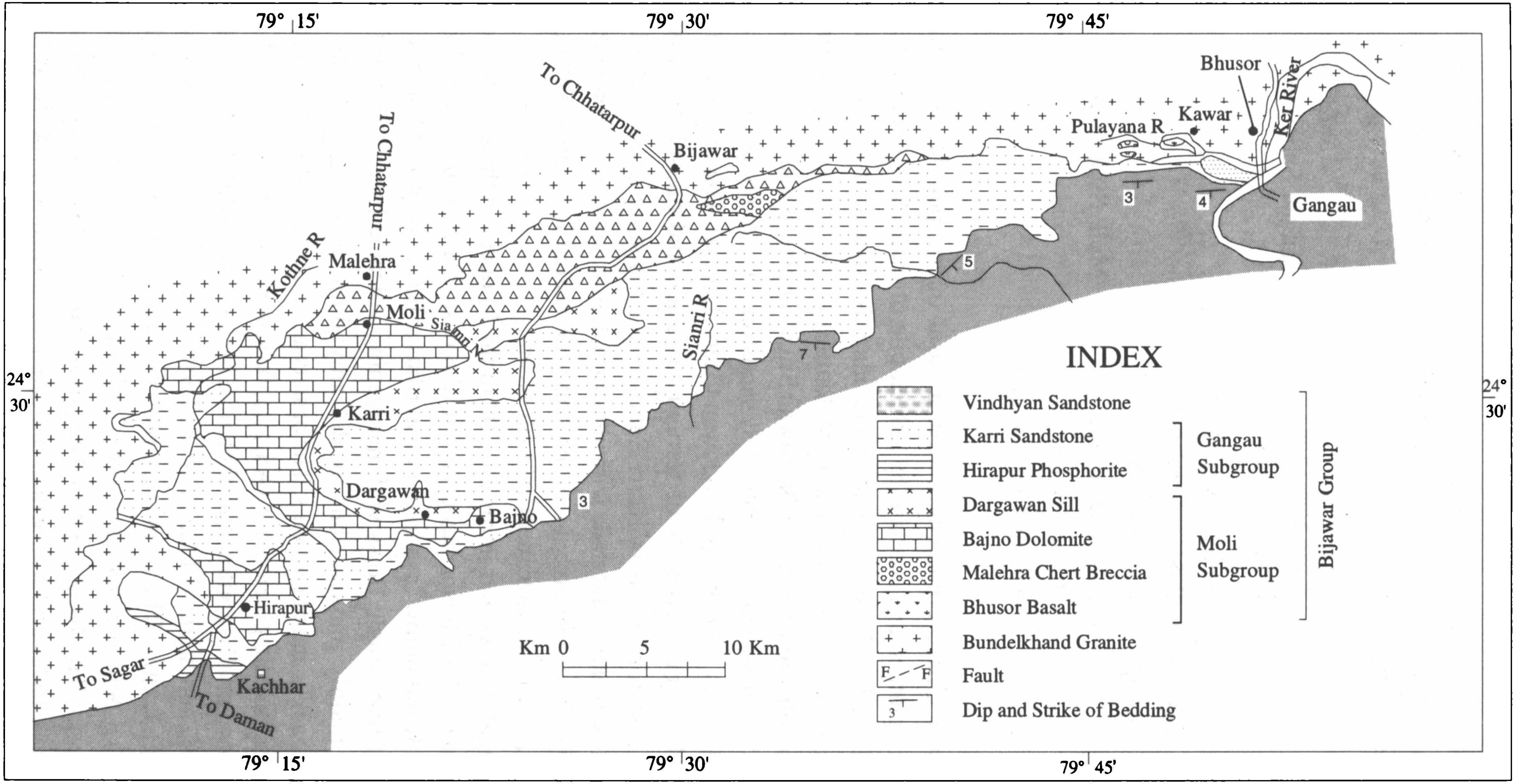
79° 15'
79° 30'
79° 45'
24° 30'
To Chhatarpur
To Chhatarpur
Bijawar
Bhusor
Kawar
Pulayana R
Ker River
Gangau
Kothne R
Malehra
Moli
Sianni N
Sianri R
Karri
Dargawan
Bajno
Hirapur
Kachhar
To Sagar
To Daman
3
4
5
7
3
Km 0 5 10 Km
INDEX
Vindhyan Sandstone
Karri Sandstone
Hirapur Phosphorite
Dargawan Sill
Bajno Dolomite
Malehra Chert Breccia
Bhusor Basalt
Bundelkhand Granite
Fault
Dip and Strike of Bedding
Gangau Subgroup
Moli Subgroup
Bijawar Group

**Fig.5.2.** Geological map of the Bijawar basin in Central India (after Kumar et al. 1990). Kurat lava is fruther west of the map area.

### Sonrai Basin

This is a 28 km long and 5 km wide, E-W trending basin situated to the west of the 'type' Bijawar basin. The sediments of the basin are folded into a large WSW-plunging syncline. The stratigraphy of the basin after R.N. Srivastava and co-workers is given in GSI (2004). The Bijawar Group of Sonrai basin consists of Sonrai Formation at the base, followed by Kurat Basalt and Solda Formation at the top. Sonrai Formation comprises basal 'grits' overlain by a variety of shales (sulphidic, graphitic and phosphatic in part) interbedded with dolomite. Phosphorite concentrations are noted at places. Pillowed and porphyritic tholeiitic basalts (Kurat Basalt), about 50 m thick, overlie the Sonrai Formation. The overlying Solda Formation consists of ferruginous quartzite and chloritic to ferruginous shale. The depositional environment is marginal marine grading into delta. Sulphidic and graphitic shales suggest local reducing environment.

### Harda Inlier

An isolated inlier of Bijawar Group consisting of gritty quartzite, ferruginous and manganiferous breccia, limestone, dolomite, shale and sandstone, together with contemporaneous basic lava flows, is exposed at Harda within the Vindhyan succession and Deccan Trap of Narmada valley. (K.K. Chhatri, *in* GSI, 2004). The sediments are deformed into two sets of folds. Galena and chalcopyrite occurrence is noted in stromatolitic dolomite at Joga.

### Gwalior Basin

Gwalior basin extends E-W for 80 km with a width of 25 km, situated near Gwalior to the north of Bundelkhand granite, almost 200 km northwest of Bijawar basin. Gwalior Group is made of a lower Par Formation (60 m) consisting of basal 'grit' and conglomerate grading into glauconitic sandstone and two layers of stromatolitic limestone, and an upper Morar Formation (650 m) comprising siliceous and ferruginous shale and chert, banded red jasper, limestone and tuffaceous sandstone. The beds are undeformed and show gentle dips (~5°). About five horizons of tholeiitic basalts and gabbroic sills (170 m) are seen within the Morar Formation. These volcanics are similar to those of Bijawar basin, but have not been studied in detail. The Gwalior lavas yield Rb-Sr isochron age of 1830±200 Ma. Rb-Sr and K-Ar ages of mafic sills in the basin are 1775-1790 Ma. Rb-Sr age of mafic dykes in Bundelkhand granite is ~1800 Ma (*see* GSI, 2004). These dates correspond to the 1700-1800 Ma age of Bijawar Group.

### Abujhmar Basin

Abujhmar basin (Fig.5.3), named for 'abujh mar' or 'unknown hills' in the remote Bastar region, covers an area of 3000 sq. km and has been studied only in recent years because of very limited accessibility (Mishra et al. 1987). Early maps show it to be a triangular basin correlatable with the other Meso-Neoproterozoic Purana basins, but recent studies have shown it to be a Palaeoproterozoic rectangular basin (100 x 30 km) with a central triangular outcrop of sandstones. The basin, according to Mishra et al. (1987), has a tail-like fault-bound extension in the southeastern part near Bodhghat Dam. The western margin of the basin is bounded by the Kotri lineament. The basin overlies the Kotri-Dongargarh orogen. The stratigraphic succession of Abujhmar Group is as follows:

| | |
|---|---|
| Abujhmar Group | Maspur Basalt (with gabbro/dolerite sills and dykes)<br>Gundul Formation |
| | ----------Unconformity------------ |
| | Nandgaon, Bailadila and Sukma Groups with surrounding gneisses/granites |

The basal conglomerate of Gundul Formation is polymictic with clasts of granite, Sukma quartzite, Bailadila BIF and Nandgaon rhyolite derived from the underlying supracrustal groups and the associated gneisses and granites. The conglomerate grades into 'grit', arkosic arenite and quartz arenite with ripple marks and cross bedding. The associated shale has local carbonaceous layers and is intercalated with siltstone. Maspur Basalt is mainly massive but locally amygdular. Basic dykes and sills intrude the basaltic sequence. These basic rocks are mainly continental tholeiitic in composition.

Abujhmar Group is unmetamorphosed, showing broad basinal dips with open folds. However, in the tail portion near Bodghat, the sediments are deformed in a shear zone and metamorphosed in greenschist facies, with sandstones becoming quartzites, shales and phyllites with 'knots' of chiastolite, and basalt converting into metabasalt. It is not, however, certain whether this metamorphosed strip belongs to the underlying Bengpal Group, rather than to Abujhmar Group.

### Papaghni Sub-basin

Papaghni sub-basin of the main Cuddapah basin is correlated with other Palaeoproterozoic basins on the basis of near-basal mafic volcanics and sills that indicate Rb-Sr isochron age of ~1800 Ma. This sub-basin is described under the Cuddapah basin.

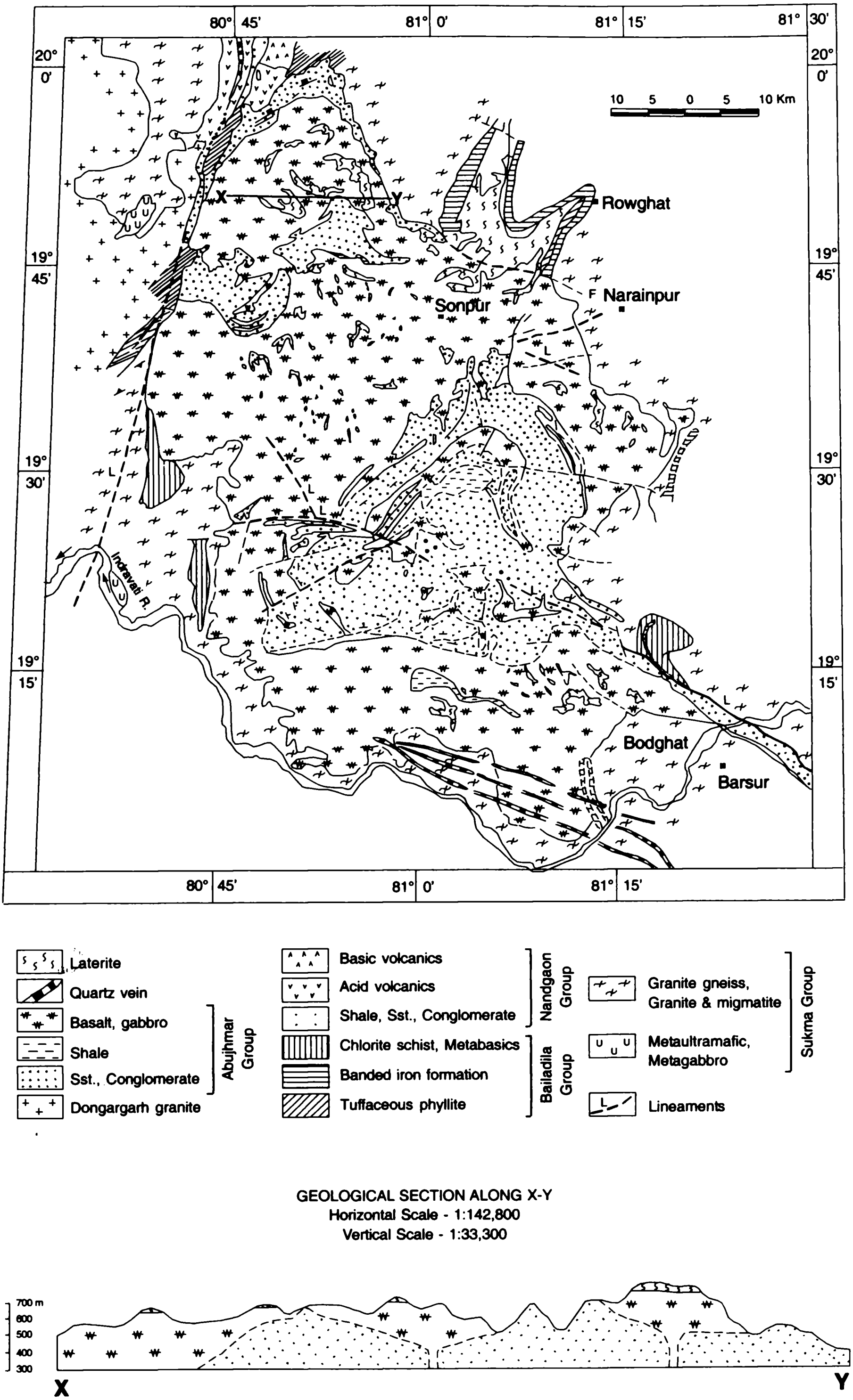
80° 45'
81° 0'
81° 15'
81° 30'
20° 0'
19° 45'
19° 30'
19° 15'
10 5 0 5 10 Km
X
Y
Rowghat
F Narainpur
Sonpur
Indravati R.
L
Bodghat
Barsur
Laterite
Quartz vein
Basalt, gabbro
Shale
Sst., Conglomerate
Dongargarh granite
Abujhmar Group
Basic volcanics
Acid volcanics
Shale, Sst., Conglomerate
Nandgaon Group
Chlorite schist, Metabasics
Banded iron formation
Tuffaceous phyllite
Bailadila Group
Granite gneiss, Granite & migmatite
Metaultramafic, Metagabbro
Sukma Group
Lineaments
GEOLOGICAL SECTION ALONG X-Y
Horizontal Scale - 1:142,800
Vertical Scale - 1:33,300
700 m
600
500
400
300
X
Y

**Fig.5.3.** Abujhmar basin of central India (after Mishra et al. 1987).

## MESOPROTEROZOIC BASINS

### Vindhyan Basin

The largest single Purana basin in the Indian Peninsular shield is the spectacular, sickle shaped, ENE trending Vindhyan basin (Fig.5.4) (also called rarely as Vindhyanchal basin after the prominent Vindhya Mountains), situated on the Bundelkhand craton. The vast basin wraps round Bundelkhand granite and covers an exposed area of 60,000 km$^2$ and a concealed area of 1,62,000 km$^2$ under the Indo-Gangetic Alluvium and Deccan Trap. The Son-Narmada (SONA) fault bounds the basin in the south and the Great Boundary Fault (GBF) in the northwest. Geographically, the basin extends from Sasaram in the east to Dholpur in the north, passing through the Son Valley, Bhopal, Dhar Forest and Chittorgarh and Sawai Madhopur areas. The Vindhyan basin is well known for its resources of diamond, limestone and dolomite, building stones and glass sand.

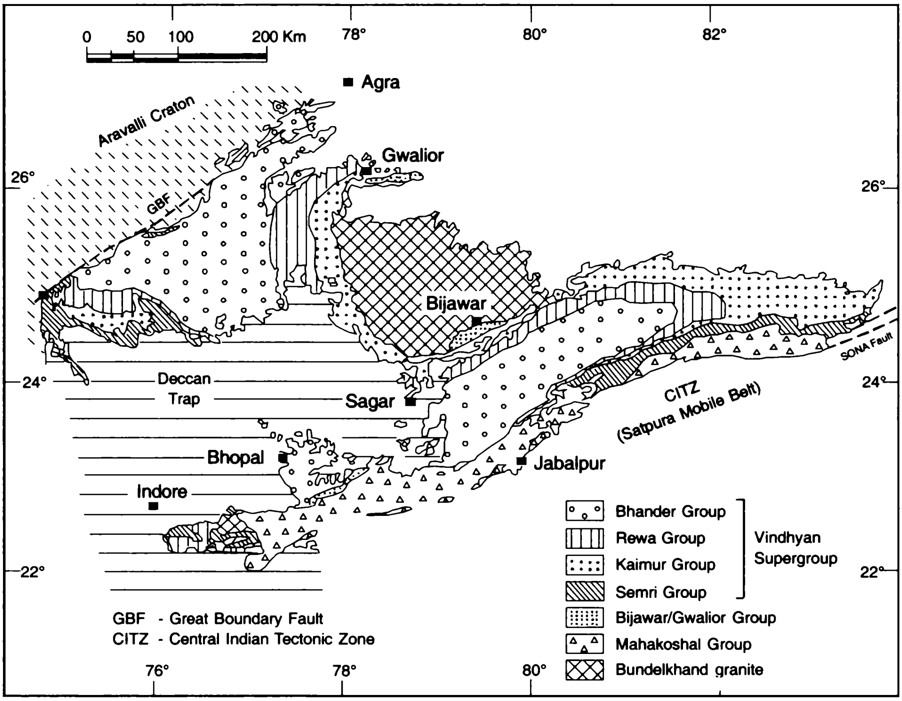
0 50 100 200 Km
78°
80°
82°
Agra
Aravalli Craton
Gwalior
26°
26°
GBF
Bijawar
SONA Fault
24°
24°
Deccan Trap
Sagar
CITZ (Satpura Mobile Belt)
Bhopal
Jabalpur
Indore
22°
22°
Bhander Group
Rewa Group
Kaimur Group
Semri Group
Vindhyan Supergroup
Bijawar/Gwalior Group
Mahakoshal Group
Bundelkhand granite
GBF - Great Boundary Fault
CITZ - Central Indian Tectonic Zone
76°
78°
80°

**Fig.5.4.** Vindhyan basin surrounding Bundelkhand craton (modified from Kale, 1991).

*Previous Studies:* The long history of studies on the Vindhyan basin commencing from the work of D.H. Williams in 1848 is described in

Soni et al. (1987). The main classifications up to 'group' level proposed by the early pioneers are still in use today. T. Oldham proposed in 1856 the three-fold division into Kaimur, Rewa and Bhander. H.B. Medlicott in 1859 introduced the term Semri for the sediments underlying the Kaimur. F.R. Mallet in 1869 designated the Semri as Lower Vindhyan, as distinct from the rest as Upper Vindhyan, and this was in vogue until recently (Srivastava et al. 1983). It is now realised that all the four groups are important and separate entities, making the distinction of Lower and Upper Vindhyan tenuous. Among the stratigraphic schemes that are currently in use are those of Sastry and Moitra (1984) and Soni et al. (1987), which were adopted by Kale and Phansalkar (1991). Prasad (1984) proposed a scheme for the Rajasthan part of the basin. Vindhyan basin displays a wide variety of depositional environments in space and time that have been studied by many workers beginning with Auden (1933). Among the important sedimentological contributions are those by Singh (1980) and the papers in Valdiya et al. (1982) and Bhattacharya (1996). Papers on various aspects of Vindhyan basin are included in the edited volumes by GSI (1981a), Valdiya et al. (1982), Zutshi and Panwar (1997), Petroleum Asia Journal, v.6(4) (1983), and Special Issue on Vindhyan Geology (Jour. Earth System Sci., v.115, No.1, pp.1-183, 2006).

## Stratigraphy

The stratigraphic scheme followed here is given in Table 5.1. A plethora of nomenclature exists at the 'formation' level in literature and many do not conform to stratigraphic codes. More important among the names are given in the parentheses in the table. Intra-basinal correlation from different geographic areas of the basin is given in Soni et al. (1987), and Kale and Phansalkar (1991) and Chakraborty (2006) have adopted some of them. The formational names given in the Table 5.1 conform to the standard stratigraphic codes.

## Description of Lithology

### *Semri Group*

Semri Group derives its name from Semri River near Bijawar and is well developed in the eastern Son valley near Sidhi and around Chittorgarh, and to some extent near Bijawar and Sawai Madhopur. The measured stratigraphic thickness near Sidhi is 3430 m, whereas elsewhere estimates vary from 20 to 4345 m. Generally, the sediments tend to thin to the west and north, and the variable thickness indicates an irregular basin floor. Semri Group rests with non-conformity on Bundelkhand and Berach granites as well as Banded Gneisssic Complex (BGC), and with angular unconformity on Bijawar Group.

**Table 5.1.** Lithostratigraphy of Vindhyan Supergroup

| Group | Formation | Alternative Names |
|---|---|---|
| Bhander Group (1300-1500 m) | Maihar Sandstone | (Upper Bhander Sst.: Divided into Bhavpura Sh., Balwan Lst. Shikaoda Sst.) |
| | Sirbu Shale | |
| | Bundi Hill Sandstone | (Lower Bhander Sst.) |
| | Lakheri Limestone | (Bhander Lst., Nagod Lst.) |
| | Ganurgarh Shale | (Simrawal Sh.) |
| - - - - - - - - - - - - - - - Disconformity/ Gradational Contact - - - - - - - - - - - - - - - | | |
| Rewa Group (100-300 m) | Govindgarh Sandstone | (Upper Rewa Sst., Gahadra Sst.) |
| | Drummondganj Sandstone | |
| | Jhiri Shale | (Variegated Sh.) |
| | Asan Sandstone | (Lower Rewa Sst., Itwa Sst., Kanar Sst.) |
| | Panna Shale | |
| - - - - - - - - - - - - - - - Normal Contact / Facies Change- - - - - - - - - - - - - - - | | |
| Kaimur Group (400 m) | Dhandraul Quartzite | (Upper Kaimur Sst., Scarp Sst.) |
| | Mangesar Formation | |
| | Bijaigarh Shale | |
| | Markundi Sandstone | (Ghaghar Sst.) |
| | Ghurma Shale | (Susnai Breccia) |
| | Sasaram Sandstone | (Lower Kaimur Sst.) |
| - - - - - - - - - - - - - - - Unconformity / Normal Contact - - - - - - - - - - - - - - | | |
| Semri Group (3000-4000 m) | Suket Shale | (Baghwar Sh.) |
| | Rohtas Limestone | (Nimbahera Lst.: Divided into Bari Sh., Jiran Sst. and Khori Malan Cong.) |
| | Chorhat Sandstone | (Glauconite Bed, Rampur Sst., Basuhari Sst., Tirohan Breccia) |
| | Bargawan Limestone | (Salkhan Lst., Fawn Lst., Chorhat Lst., Tirohan Lst.) |
| | Kheinjua Shale | (Olive Sh., Koldaha Sh., Binota Sh.) |
| | Chopan Porcellanite | (Deonar Porc.) |
| | Kajrahat Limestone | (Kuteshwar Lst., Bhagwanpura Lst., Tirohan Lst., Lohar Dol.) |
| | Arangi Shale | |
| | Deoland Sandstone | (Khardeola Sst., Pandwafall Sst.) |
| - - - - - - - - - - - - - Angular Unconformity / Non-conformity- - - - - - - - - - - - - | | |
| Granites and Supracrustals | | |

Sst. - Sandstone; Sh. - Shale, Lst. - Limestone, Dol. - Dolomite, Porc. - Porcellanite, Cong. - Conglomerate

The basal succession consists of conglomerate, cross-bedded ferruginous sandstone and shale, exposed mainly in Rajasthan (Khardeola Sandstone). The status and significance of Khairmala volcanics and pyroclastics at the base of the sequence in Rajasthan (*see* Raza et al. 2001) is yet to be fully understood. It may be part of Hindoli Group that underlies the Vindhyan succession elsewhere. In Bundelkhand and Son valley, the basal unit consists of sandstone (Deoland or Pandwafall Sandstone), overlain by shale (Arangi Shale). The sandstone is glauconitic with lenses of chert and limestone suggesting transgressive marine environment. Matrix-poor, debris flow conglomerate forms part of Deoland Sandstone (Fig.5.5a). The maturity of the sandstone, according to some, suggests instead a fluvial environment. The overlying stromatolitic limestone and dolomite (Kajrahat/Tirohan Limestone and Lohar Dolomite) containing illite and kaolinite suggest a continental shelf setting.

The basal succession is overlain by felsic volcanics (Chopan/Deonar Porcellanite), consisting of rhyolitic crystal-, vitric- and pumice-tuff, agglomerate, breccia and bedded chert (Srivastava et al. 2001). Volcanic bombs and lapilli are also seen. Locally, felsite sills are also noticed. Parallel and rippled lamination in pyroclastic rocks is conspicuous (Fig.5.5b). Presence of native sulphur and pyrite in black shale indicates volcanic, euxenic environment. The associated *Conophyton* bearing limestone, lime-chert conglomerate and turbidite suggest deep-water slope to basinal environment. The overlying Olive Shale (Kheinjua Shale), Fawn Limestone (Bargawan Limestone) and glauconitic siltstone (Chorhaṭ Sandstone) suggest a composite environment (Fig.5.6). Similar environments were visualised for Rohtas Limestone and Suket Shale, but other workers suggest a lagoonal environment instead.

### *Kaimur Group*

Kaimur Group, named after the Kaimur scarp, has conformable contact with Semri Group in Son valley and Chittorgarh, but has angular unconformable contact at Kalinjer Fort. The Pipartola, Bundi and Dulchipur conglomerates separate both the groups in western Bundelkhand and Rajasthan. The presence of clasts of Semri sandstone and shale in the basal conglomerate suggests significant time gap.

Kaimur Group is essentially a sandstone-shale association, as against the shale-limestone association of Semri Group. The basal Sasaram Sandstone overlain by Markundi Sandstone and intervening silicified shale (Ghurma Shale or Susnai Breccia) are interpreted as products of either high velocity coastal streams or barrier beach dune or tidal flat. The carbonaceous (77% ash) Bijaigarh Shale is interpreted as a swamp deposit, but the pyritiferous shale with pyrite beds near Amjhor (40% S) suggests quiet water or lagoonal deposit. The

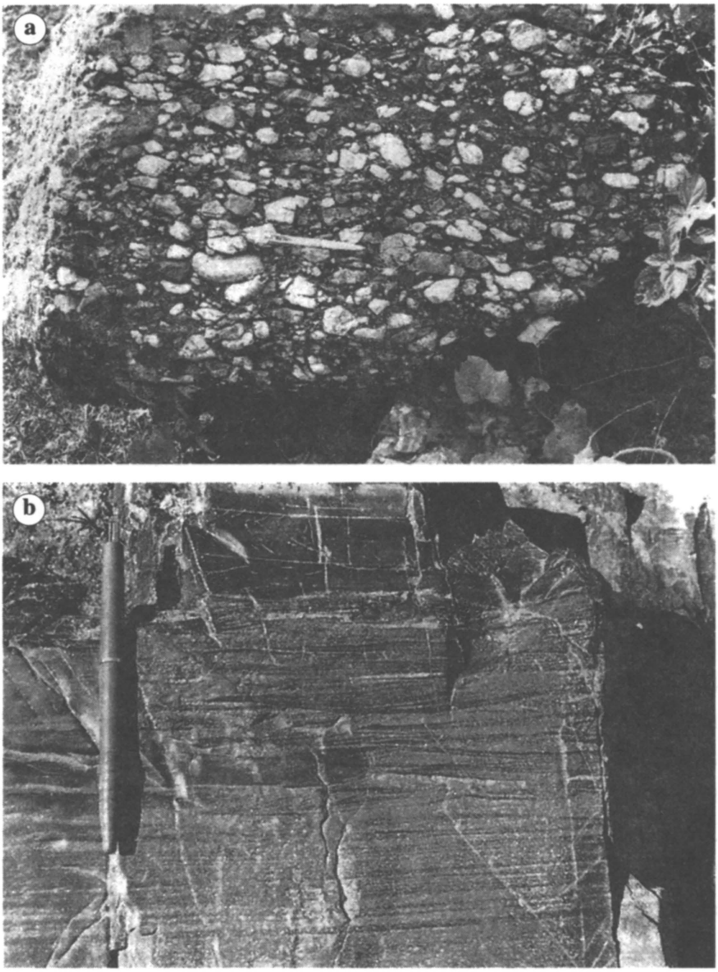

**Fig.5.5.** (**a**) Matrix poor, debris flow conglomerate of Deoland Sandstone (Chakraborty and Bhattacharyya, 1996). (**b**) Parallel lamination followed by ripple lamination in a fine-grained pyroclastic rock, Deonar Porcellanite, Semri Group (Chakraborty et al. 1996).

overlying Dhandraul Quartzite consisting of arkosic sandstone, with associated pebble beds and shale (Mangesar Formation), is visualised as a braided ephemeral stream deposit or as sandy intertidal flat or tidal channel deposit.

### *Rewa Group*

Rewa Group, named after the erstwhile Rewa State, is characterised by frequent lateral facies change and is best exposed around Satna, Shivapuri and Chittorgarh. The sediments thicken to the north indicating deepening of the basin. Rewa Group is also well developed in Harda Inlier near Hoshangabad, known in earlier literature as Dhar Forest area.

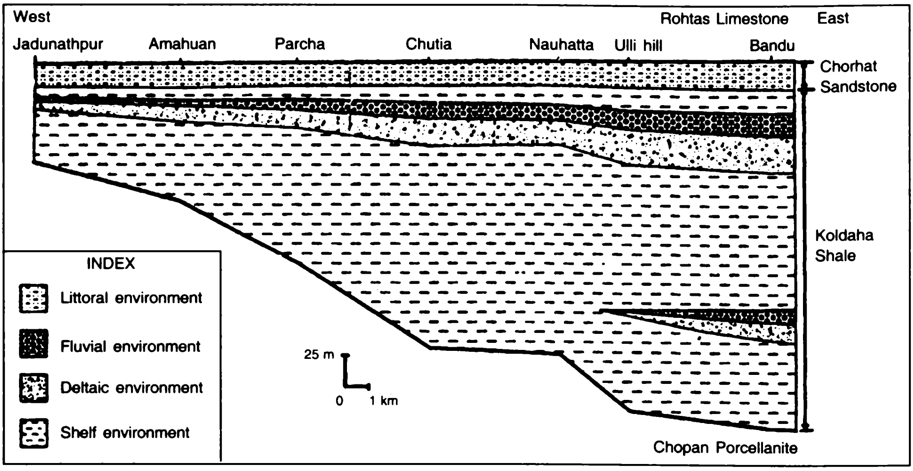
West
East
Rohtas Limestone
Jadunathpur
Amahuan
Parcha
Chutia
Nauhatta
Ulli hill
Bandu
Chorhat Sandstone
Koldaha Shale
Chopan Porcellanite
INDEX
Littoral environment
Fluvial environment
Deltaic environment
Shelf environment
25 m
0
1 km

**Fig.5.6.** Composite environments in Kheinjua (after Banerjee and Jeevan Kumar, 2003).

The basal Panna Shale, without any basal conglomerate, indicates continuity of deposition from Kaimur Group. Red shale, limestone, barytes and glauconitic siltstone (Panna Shale and Asan Sandstone) indicate lagoonal environment. The coarsening upward sandstone with mudcracks suggests periodical exposure. The overlying Jhiri Shale is separated from Asan Sandstone by a diamondiferous conglomerate at Panna. Elsewhere the contact is gradational between sandstone and shale. Mudcracks and rain prints in the shale indicate subaerial conditions. Red shale, with glauconitic siltstone containing authigenic felspars, is interpreted to indicate lagoonal, lacustrine or offshore environment. The next unit of Drummondganj Sandstone is deposited in shoreface environment. The overlying Govindgarh Sandstone is poorly sorted, pebbly and texturally immature, indicating either fluvial, deltaic or near shore muddy tidal flat environment.

### *Bhander Group*

Bhander Group, named after Bhander Upland, is extensively developed along the axis of the basin and in the Bhopal Inlier within the Deccan Trap, and is conspicuous for lateral pinching and swelling. The basal unit of Ganurgarh Shale has the diamondiferous conglomerate in Panna area, but elsewhere the contact is gradational with Rewa Group. The Ganurgarh chocolate shale with stromatolitic limestone and sandstone interbeds that contain intraformational breccia, halite casts, and scour and fill structures, are indicative of shoreline-lagoon-tidal flat complex. The finely laminated, micritic Lakheri Limestone with algal mats and stromatolites, desiccation structures, gypsum layers and rare ooids suggests an evaporitic environment. Elsewhere, the limestone has formed in tidal flat-lagoon environment.

The overlying Bundi Hill Sandstone is a fining upward transgressive deposit characteristic of tidal flat, but elsewhere it is a sheet sandstone with heavy mineral layers suggestive of barrier beach or tidal inlet. Storm deposits are also suggested from sedimentary structures in this sandstone at other places. The overlying purple Sirbu Shale with halite casts indicates oxidising to arid conditions. The top unit of Maihar Sandstone is a blanket deposit with ripple marks, cross bedding and load casts, and is intercalated with stromatolitic limestone beds, suggesting an overall tidal flat to near shore littoral environment. Elsewhere, fanglomerates are associated with the sandstone where palaeocurrent directions show wide dispersal indicating fluvial to deltaic environment. Recent opinion favours a mixture of tidal and aeolean regimes for this sandstone-shale-sandstone-stromatolitic limestone depositional sequence.

### Structure

The major structure of Vindhyan basin is a synclinorium with the axis curving along the middle of the sickle-shaped basin. The Bundelkhand granite dome and the constricting SONA fault in the southeast and Great Boundary Fault in the northwest control the configuration of the basin. Low amplitude open anticlines and synclines and doubly plunging folds are common, giving rise to rolling dips. Minor folds are fairly common. Only a single phase of deformation is visualised because of lack of fold interference patterns, but some opine that there may be two phases of deformation, particularly in the western exposures. In the vicinity of major faults bounding the basin, the sediments are tightly folded with the development of overturned folds and high angle reverse faults. There are well-known domes like the Jabera and Ramgarh domes, caused either by the vertical uplift of the basement or doming up probably caused by a deep-seated pluton.

### Age

Recent robust dating has fixed the beginning of Vindhyan sedimentation around 1600-1720 Ma (*see* Ray, 2006). Kajrahat Limestone has given Pb-Pb isochron age of 1720 Ma. Silicified tuffs of Kheinjua Formation (Semri Group) are dated by SHRIMP U-Pb zircon method at 1628±8 Ma and 1599±8 Ma. Felsic volcanics of Chopan/Deonar Porcellanite (Semri Group) provide a zircon U-Pb age of 1632 Ma. The kimberlites of Panna yield Rb-Sr ages of 1067±31 Ma, 1140±20 Ma and 1130±20 Ma, which suggest the age of Kaimur Group to be about 1100-1150 Ma. Zircon ages of Bhander Group are ~1020 Ma. The time span of Vindhyan basin is between 1600 and 1000 Ma, a period of 600 m.y. that is punctuated by four major unconformities marking significant breaks, indicating that the sedimentation was episodic over a long period (Kale, 1991; Chaudhuri et al. 2002). These data indicate a Mesoproterozoic age for the Vindhyan, disputing the Neoproterozoic age for the upper Vindhyan (Malone et al. 2008).

### Life

There is a large volume of literature on the life in the Vindhyan period. Venkatachala et al. (1996), Kumar (2003) and De (2006) provide summaries of life in the Vindhyan period. The evidence of life is either direct (mega- and micro-fossils) or indirect (stromatolites, trace fossils, algal mats etc). Among the important megafossils are the various species of *Chuaria* and *Tawuia* and their equivalents in the Semri, Rewa and Bhander Groups. These also include carbonaceous forms, their impressions and pseudomorphs. Microfossils reported from Semri and Bhander Groups include a variety of cynobacterial, bacterial, algal, fungal and acritarchal remains. Most of the microfossils do not have any chronological significance, except possibly a few like *Obruchevella* species that suggest Upper Riphean (600-950 Ma) age for the Lakheri Limestone and Bundi Hill Sandstone of Bhander Group. Stromatolites are abundant in the Vindhyan record, but they have a long time range and hence have only a limited correlative value. Particularly, the columnar and conical stromatolites do not provide clear time constraints, but the branched forms seen in Bhander Group may suggest Upper Riphean (600-950 Ma) age.

Several instances of small shelly fauna, primitive brachiopods and Ediacaran fauna like *Spriggina* as well as trace fossils (e.g., triploblastic animal burrows) are reported recently from Semri Group, to suggest that the Vindhyan extends into the Cambrian. Several studies, which followed these sensational reports, have shown them to be non-fossils or dubio-fossils (*see* "Vindhyan Fossil Controversy"; Jour. Geol. Soc. India, v.55, pp.675-680, 2000 and references therein). Recently Ediacaran fossils are reported from the Bhander Group (De, 2006a) and the controversy persists (Azmi et al. 2008).

### Palaeogeography

Seismic studies have shown that the Vindhyan basin extends far north under the Ganga alluvium, as two arms around the median Faizabad Ridge (Fig.5.7a). Horst and graben structures, which played a major role during Vindhyan sedimentation, have resulted in the formation of many sub-basins. In Ganga valley, the sediment thickness is estimated at 6.0 to 6.5 km, whereas

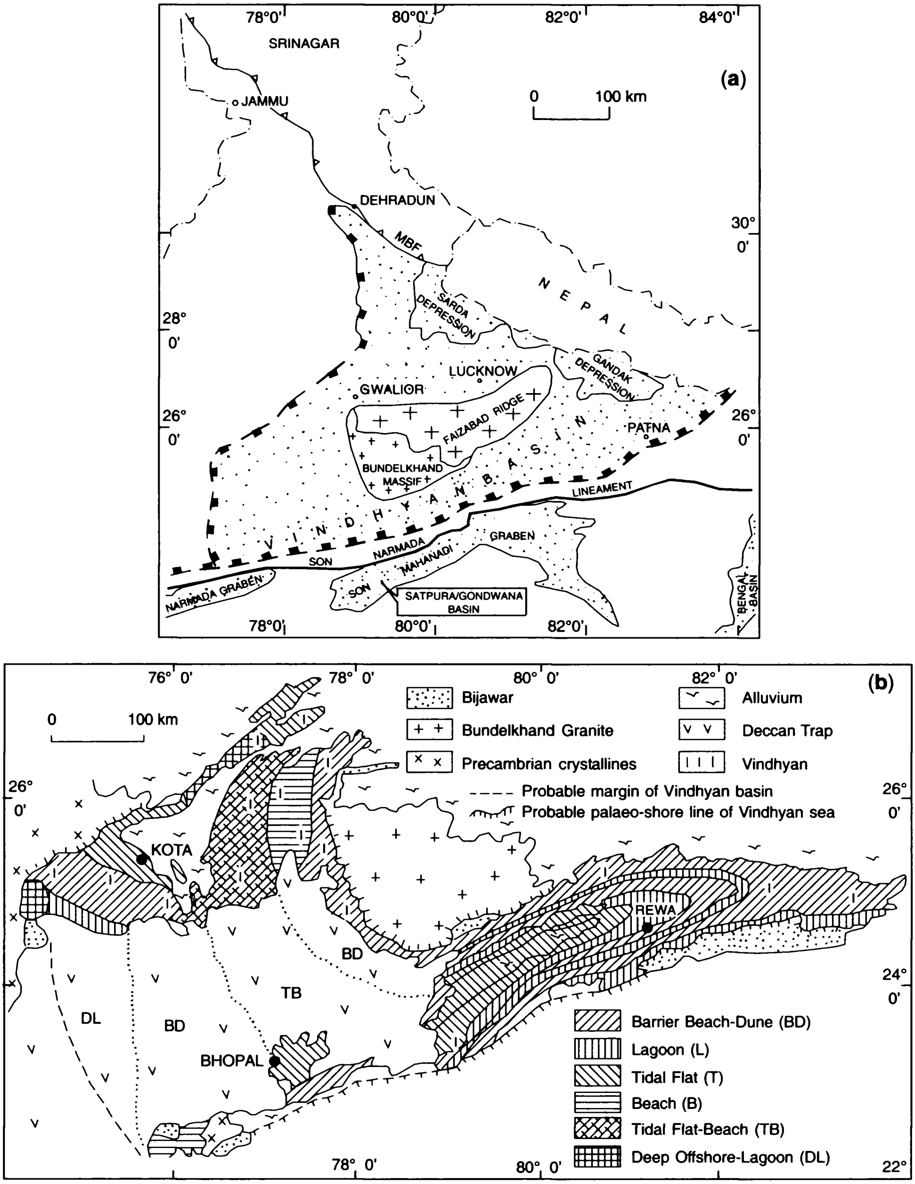
78°0'
80°0'
82°0'
84°0'
SRINAGAR
(a)
JAMMU
0
100 km
DEHRADUN
MBF
30° 0'
NEPAL
SARDA DEPRESSION
28° 0'
LUCKNOW
GWALIOR
FAIZABAD RIDGE
GANDAK DEPRESSION
26° 0'
PATNA
BUNDELKHAND MASSIF
VINDHYAN BASIN
LINEAMENT
SON
NARMADA
GRABEN
MAHANADI
NARMADA GRABEN
SON
SATPURA/GONDWANA BASIN
BENGAL BASIN
78°0'
80°0'
82°0'
76° 0'
78° 0'
80° 0'
82° 0'
(b)
0
100 km
Bijawar
Bundelkhand Granite
Precambrian crystallines
Alluvium
Deccan Trap
Vindhyan
Probable margin of Vindhyan basin
Probable palaeo-shore line of Vindhyan sea
26° 0'
KOTA
REWA
BD
TB
DL
BHOPAL
24° 0'
Barrier Beach-Dune (BD)
Lagoon (L)
Tidal Flat (T)
Beach (B)
Tidal Flat-Beach (TB)
Deep Offshore-Lagoon (DL)
22° 0'

**Fig.5.7.** (**a**) Map showing depositional limit of Vindhyan basin. (**b**) Depositional environments of Vindhyan basin (after Srivastava et al.1983).

in the Himalayan slopes to the north, it is about 4.0 to 4.5 km. Palaeocurrent data on a regional scale shows palaeoslope to the north and northwest, which corresponds to the increase in sediment thickness under Ganga alluvium of 6.5 km from 4.5 km within the basinal outcrops. There is a possibility that the Vindhyan shallow sea was connected to the main sea in the northwest. Comparisons of the Vindhyan strata with those in the lesser Himalaya have been made by some workers on the basis of lithological similarities and presence of stromatolites (*see* Valdiya et al. 1982), but these correlations need to be confirmed by detailed multi-disciplinary studies. There is also a need for more intensive study of palaeoenvironments of the Vindhyan sediments, since the present knowledge indicates a wide spectrum of environments from fluvial through aeolian to shallow and deep seas (Fig.5.7b).

### Chhattisgarh Basin

Chhattisgarh basin (Fig.5.8) is the largest Purana basin in Bastar craton. The craton is dotted with several smaller basins like Khariar, Ampani, Indravati and Sabari (Sukma), besides many outliers like Keskal, Singanpur and Chedrapal. Although Kale (1991) believed that each Purana basin is unique with well-defined boundaries and not an erosional remnant or atectonic depression, the prevailing opinion is that the isolated basins and outliers in Bastar craton are part of once-continuous basin fill that got fragmented by basement doming and denudation (Ahmad, 1958; Ramakrishnan, 1987; Chaudhuri et al. 2002).

Chhattisgarh basin covering an area of about 36000 km$^2$ is situated on the northern edge of Bastar craton. It is bounded by the Kotri-Dongargarh orogen in the west, Satpura mobile belt in the north, Gondwana graben of Mahanadi in the northeast and the Eastern Ghats mobile belt in the southeast. In the south, the basin overlies the basement gneiss enclosing the Sonakhan greenstone belt. Chhattisgarh basin is the third largest Purana basin after the Vindhyan and Cuddapah, and extends for about 300 km in the E-W and 200 km in the N-S directions, with an irregular rectangular configuration. Vast limestone and dolomite resources of the basin feed the Bhilai Steel Plant and the cement factories in the vicinity. The granitic terrain surrounding the basin has been recently found to host a number of kimberlite pipes.

Pioneering geological work in the basin was carried out by V. Ball, W. King and F.D. Smith, followed by N.V.B.S. Dutt in 1964 and W.A. Schnitzer in 1971. Murti (1987, 1996), Das et al. (1992, 2001), Chaudhuri et al. (2002) and Patranabis-Deb (2004) provide recent geological summaries of the basin. The basin contains about 2500 m thick sediments of orthoquartzite-carbonate-pelite suite, deposited in multiple sedimentary cycles, intercalated with minor felsic volcanics and pyroclastics and punctuated by unconformities. Each cycle starts with arenaceous facies and ends up with shale-limestone facies. The basin is divided into two sub-basins, the Hirri in the west and Baradwar in the east separated by the Sonakhan high over the Sonakhan greenstone belt. Two small proto-basins containing the oldest sequences occur in the east at Singhora and Barapahar.

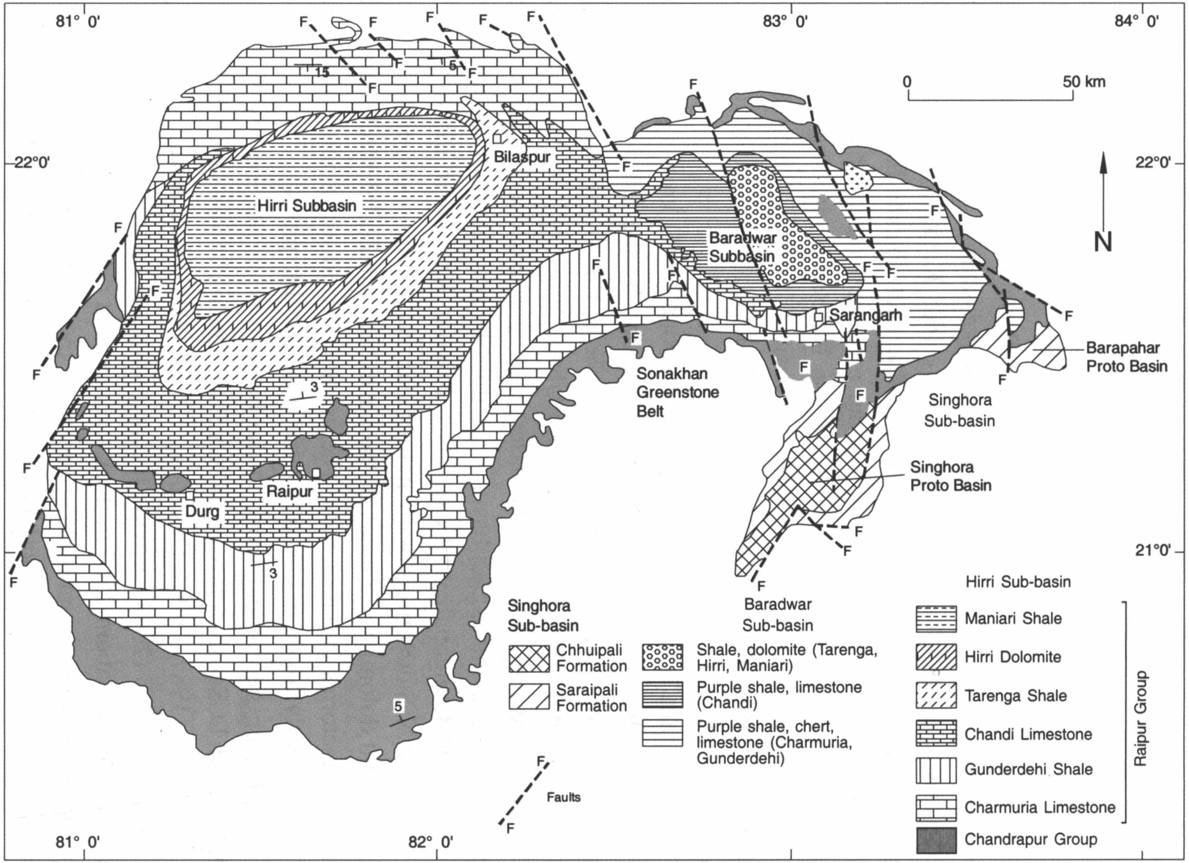
81° 0'
83° 0'
84° 0'
22°0'
21°0'
82° 0'
0
50 km
N
F
15
5
3
Bilaspur
Hirri Subbasin
Baradwar Subbasin
Sarangarh
Sonakhan Greenstone Belt
Raipur
Durg
Barapahar Proto Basin
Singhora Sub-basin
Singhora Proto Basin
Singhora Sub-basin
Chhuipali Formation
Saraipali Formation
Baradwar Sub-basin
Shale, dolomite (Tarenga, Hirri, Maniari)
Purple shale, limestone (Chandi)
Purple shale, chert, limestone (Charmuria, Gunderdehi)
Hirri Sub-basin
Maniari Shale
Hirri Dolomite
Tarenga Shale
Chandi Limestone
Gunderdehi Shale
Charmuria Limestone
Chandrapur Group
Raipur Group
Faults

**Fig.5.8.** Generalised geological map of Chhattisgarh basin (after Das et al. 1992).

The generalised stratigraphy of the Chhattisgarh basin after Das et al. (1992) and Patranabis-Deb (2004) is given in Table 5.2.

**Table 5.2.** Lithostratigraphy of Chhattisgarh Supergroup

| Group | Formation (thickness in m) | Lithology |
|---|---|---|
| Raipur Group (1900 m) | Maniari Shale (70) | Purple shale, dolomite, gypsum |
| | Hirri Dolomite (70) | Grey dolomite |
| | Tarenga Shale (180) | Dolomitic shale, shale-chert beds, purple shale, limestone |
| | Chandi Limestone (670) | Stromatolitic dolomite, limestone, glauconitic sandstone, shale |
| | Gunderdehi Shale (430) | Shale with limestone interbeds, arenite-shale, ignimbrite |
| | Charmuria Limestone (490) | Phosphatic limestone with shale interbeds, cherty limestone and phosphatic dolomite, chert-shale interbeds |
| | Bijepar Shale (100) | Green and brown calcareous shale with sandy interbeds |
| Chandrapur Group (400 m) | Kansapathar Sandstone (200) | Glauconitic sandstone |
| | Chaporadih Shale (200) | Shale with arenite interbeds |
| | Lohardih Conglomerate (20) | Purple arkose, gritty arenite and basal conglomerate |
| | ---------------Unconformity--------------- | |
| Singhora Group (400 m) | Chhuipali Shale (300) | Shale with chert, limestone, dolomite, siltstone |
| | Bhalukona Sandstone (20) | Sandstone, siltstone, minor shale |
| | Saraipali Shale (60) | Variegated shale with siltstone, limestone, porcellanite, felsic tuff |
| | Rehatikhol Conglomerate (20) | Felspathic arenite, arkose and basal conglomerate |
| | ---------------Nonconformity--------------- | |
| | Crystalline basement of Bastar craton | |

## Description of Lithology

The basement in the south of the basin consists of gneisses, Kanker-Mainpur granitoids and Sonakhan greenstone belt. To the northeast lies the Sambalpur granite. The Bilaspur-Raigarh-Sarguja supracrustals underlie the Chhattisgarh sediments partly unconformably and partly in faulted contact with Satpura mobile belt. In the west, the Dongargarh sequence and Chilpi Group of the Kotri-Dongargarh orogen underlie the basin with a partly faulted and partly unconformable contact. In the southeast, the margin is sheared at the contact with the marginal zone of Eastern Ghat mobile belt.

The oldest Singhora Group is exposed in the Singhora proto-basin in the southeast and the Barapahar sub-basin in the northeast. The basal fining up arenaceous and rudaceous sequence (Rehatikhol Conglomerate) appears to be a fluvial fan deposit. Palaeocurrent data indicate convergence towards the basin centre to the WSW from the east and to the SE from the west. The overlying Saraipali Shale is a tidal flat sediment that is associated with contemporaneous felsic volcanism. Bhalukona Sandstone is probably a shoreline sediment, overlain by the shale-chert-stromatolitic limestone-dolomite association of Chhuipali Shale that is deposited in a shallow offshore environment.

A major hiatus followed the deposition of Singhora Group. The hiatus is succeeded by a conglomerate and coarse arkosic sandstone in a shale-dominated sequence of Chandrapur Group, followed by a limestone-shale dominated sequence of Raipur Group. Stratigraphic analysis suggests that Chandrapur Group is a proximal deposit, and Raipur Group is its distal facies equivalent. Chandrapur Group consists of three sandstone intervals, separated by two mud-dominated sequences. The basal conglomerate is interpreted either as an alluvial fan-fan delta deposit suggesting fault-controlled sedimentation in a rift basin, or as a beach deposit with sandstone lenses resulting from storms. Choparadih (Gomarda) Shale is interpreted to have a variable setting from prodelta and prograding shelf to intertidal-lagoonal zone. Kansapathar Sandstone is a storm-tide influenced shoreface and shelf deposit.

Raipur Group conformably overlies Chandrapur Group and consists of three carbonate-shale cycles. The succession commences with a brown calcareous shale and green shale about 100m thick and is designated as Bijepar Shale. The succeeding unit of Charmuria (Sarangarh) Limestone has a lower member of mixed carbonate-siliciclastic succession deposited in a shallow platform affected by storms, and an upper member of pelagic limestone grading into the deep water Gunderdehi Shale. The pelagic deposits contain channels filled with slumped limestone, limestone-clast bearing debris flow conglomerate, sandy turbidite and seismoturbidite, suggestive of tectonic perturbation in the basin. The rapid transition from the platform to pelagic sediments points to an abrupt deepening of the basin. A black limestone unit that signifies anoxic environment marks the peak of transgression of the sea. Gunderdehi Shale contains thick horizons of ignimbrite interbedded with welded tuff. The analysis of magmatic garnet in welded tuff suggests the origin of felsic material by partial melting of the lower crust at 30-35 km. The overlying shale-chert beds, phosphatic limestone, porcellanite and tuffs (Chandi Limestone and Tarenga Shale) are formed in a tidal flat, followed by a coarsening upward regressive cycle. Renewed transgressions and regressions are seen in the chert-shale-limestone-evaporite and sandstone cycles (Hirri Dolomite and Maniari Shale). The presence of gypsum in Maniari Shale indicates supratidal environment of coastal sabkha. Raipur Group is believed to be deposited in two separate basins Hirri and Baradwar, separated by the Sonakhan high.

The disposition of the proximal and distant facies belts and palaeocurrent directions indicate palaeoslope towards NNW. Signatures of storm and tidal currents suggest open marine circulation along a seaway in the north, probably located at the present site of the Son-Narmada trough. The presence of fan-delta succession at the base, followed by thick sandstone-mudstone successions, welded tuff in shale units and carbonate platform grading into pelagic environment suggest deposition in a continental rift without major hiatuses (Patranabis-Deb, 2004).

### Basic Dykes

Basic dykes intrude the sedimentary sequence at different levels in many places. The ages of these dykes (which are dominantly concentrated along the western parts of the basin) is an open question. It is not yet certain whether they are Proterozoic or Gondwana dykes.

### Structure and Tectonics

Sub-horizontal beds occupy the entire basin showing rolling dips. Anticlinal folds abutting against a fault are seen in the northern margin of the basin near Ratanpur. The eastern projections of the basin are deformed at their margins due to the impact of Eastern Ghats orogeny. Granitic domes are locally seen as at Kharsia. Basin inversion was initiated by top-to-south transport of the distal assemblage over the proximal assemblage across an ENE trending thrust. The thrust was later offset by numerous N-S trending faults, which are rejuvenated as reverse faults, bringing up slices of granitic basement and pointing to strong E-W shortening (Chaudhuri et al. 2002).

### Evidence of Life

Stromatolites show prolific development in Chhattisgarh basin, and two assemblages belonging to the Middle and Upper Riphean are recognised. Microbiota reported so far include prokaryotic cyanobacteria (mostly filamentous), unidentified algal remains and acritarchs. The age of Chhattisgarh basin is not well constrained, but SHRIMP zircon ages of ignimbrite from Raipur Group show a span of 990-1020 Ma (Patranabis-Deb et al. 2007;

Basu et al. 2008). In comparison with the other Purana basins, a time span between 1600 and 1000 Ma may be visualised for Chhattisgarh basin.

## Khariar Basin

Khariar Basin (Fig.5.9) is an irregular, oval-shaped basin occupying the N-S trending Nawagarh-Khariar plateau, covering an area of 1500 km$^2$ and containing 1000 m thick sediments. The basin, also called Noagarh

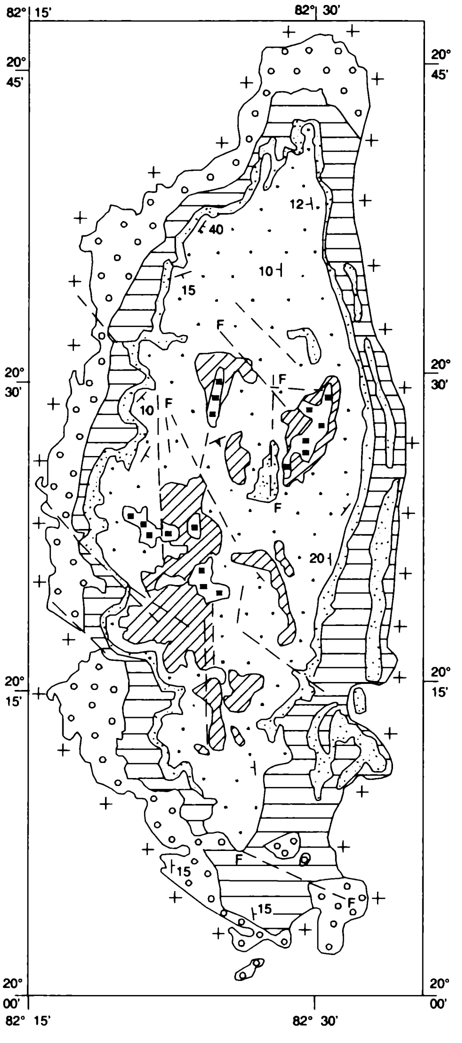

**Fig.5.9.** Geological map of Khariar basin (from Das et al. 2001). **1** - Granitoids, **2** - Devdahra Sandstone, **3** - Kulharighat Limestone, **4** - Neor Sandstone, **5** - Galighat Sandstone, **6** - Tarjhar Shale, **7** - Ling Dongri Sandstone.

(Nawagarh) basin, occupies the eastern part of Bastar craton and is juxtaposed against the faulted marginal zone of the Eastern Ghats mobile belt. On the western side, the basin is underlain by the Kanker-Mainpur granitoids containing enclaves of supracrustals, like BIF, mica schist, amphibolite and pillowed metabasalt. Small bodies of alkali granite and leucogranite are also seen in the granitic terrain in the west. Kimberlites intrude the basement in the vicinity.

The stratigraphy of the Khariar basin is given in Table 5.3. The sediments of the basin are called the Pairi Group after Pairi River that originates in the Khariar plateau (Das et al. 2001).

**Table 5.3.** Lithostratigraphy of Khariar basin

| | |
|---|---|
| Pairi Group (600-1000 m) | Ling Dongri Sandstone (60-120 m) |
| | Tarjhar Shale (205 m) |
| | Galighat Sandstone (150-300 m) |
| | - - - - - Disconformity - - - - - - - |
| | Neor Sandstone (40-160 m) |
| | Kulharighat Limestone (80-120 m) |
| | Devdahra Sandstone (10-80 m) |
| | - - - - - Unconformity - - - - - - - |
| | Crystallines of Bastar craton |

The basal sandstone unit (Devdahra Sandstone) consists of conglomerate, overlain by thick-bedded glauconitic sandstone interbedded with pyritiferous black shale and arenite. Cross bedding and mud cracks are common in this formation, indicating shallow marine environment. The overlying Kularighat Limestone is essentially a black shale-chert unit with porcellanite, pyritiferous limestone, calcareous shale and stromatolitic limestone. Deep marine euxenic condition indicated by the limestone has given way later to tidal flat environment marked by grey cross-laminated sandstone with lenticles of carbonaceous shale (Neor Sandstone).

Galighat Sandstone overlies the Neor Sandstone with a disconformity and consists essentially of a cream coloured coarse arenite with gritty and pebbly interbeds as well as siltstone intercalations. The southern part of the formation contains numerous shale and siltstone interbeds. Profuse development of shallow water sedimentary structures suggests littoral environment, with deeper sections in the southern part. Tarjhar Shale is a purple shale-siltstone unit, which grades into wacke-arenite association, suggesting an unstable shelf interlude. The top unit of Ling Dongri Sandstone is a ferruginous sandstone suggesting deposition under arid conditions.

Palaeocurrent directions vary from north to south in the lower part of the sequence, changing over to east and southeast in the upper part. Stromatolites indicate Lower to Upper Riphean age, but no radiometric data are available.

Pairi Group is involved in open to tight asymmetrical folding trending NW-SE with dips of 5 to 25°. Two phases of nearly coaxial refolding are visualised to explain some doubly plunging folds. At the eastern margin, the beds are involved in major faulting and local shearing. Clastic dykes are noticed in the basement granites in the vicinity, suggesting the link between Khariar and Chhattisgarh basins. Kimberlites intruding the basement in the west contain xenoliths of Khariar sediments.

### Ampani Basin

Ampani basin occupying an area of 220 km$^2$ on a small plateau south of Khariar near Ampani consists of a 280 m thick sandstone-shale sequence. The stratigraphy worked out by Balakrishnan and Mahesh Babu (1987) represents a basal conglomerate (2 m), followed by subarkosic sandstone (180 m), siltstone (20 m) and purple shale with calcareous interbands (70 m). The basal conglomerate unconformably overlies the Bastar granitoids containing quartz-mica schist enclaves. The basin is gently folded in the main, but along the deformed eastern margin overturned isoclinal folds and sheared boundary fault are seen. The sediments are domed up around hornblende granodiorite at Khaligarh, which is thought to be intrusive.

### Outliers

Keskal and Singanpur outliers, made of basal conglomerate, prominent sandstone and minor shale, provide an erosional link between Ampani basin in the north and Indravati basin in the south.

### Indravati Basin

Indravati basin (Fig.5.10) is an irregular rhomboid basin covering an area of 900 km$^2$ and containing orthoquartzite-shale-carbonate sequence of about 500 m thick on the average. Cement grade limestone and dolomite are important economic minerals. A few kimberlite bodies are recently located around Tokapal. The basin was mapped by H. Crookshank and P.K. Ghosh in the thirties, and by N.V.B.S. Dutt, K.V.J.R. Kripanidhi and V.P. Sharma in the sixties. The stratigraphy worked by Ramakrishnan (1987) of the Indravati Group (350-550 m) is given in Table 5.4.

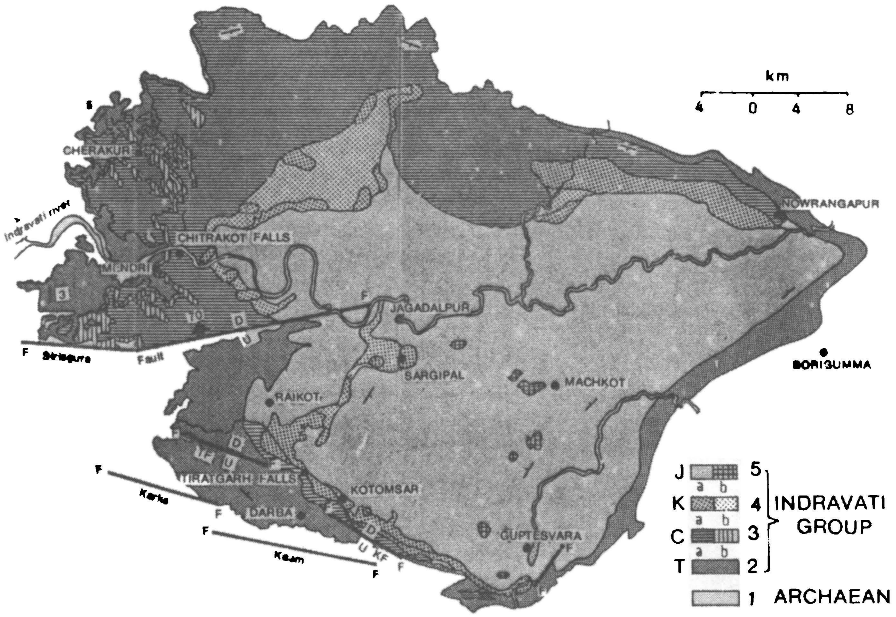
km
4 0 4 8
CHERAKUR
Indravati river
CHITRAKOT FALLS
MENDRI
JAGADALPUR
NOWRANGAPUR
BORIGUMMA
F Sribegura Fault
SARGIPAL
MACHKOT
RAIKOT
TIRATGARH FALLS
KOTOMSAR
DAHBA
GUPTESVARA
Karka
Kesam
F
J a b 5
K a b 4
C a b 3
T 2
INDRAVATI GROUP
1 ARCHAEAN

**Fig.5.10.** Geological map of Indravati basin (after Ramakrishnan, 1987). **1** - Archaean granite basement, **2** - Basal arkose, conglomerate and orthoquartzite of Tiratgarh Formation (T), **3a** - Purple shale and **3b** - Arenaceous intercalations of Cherakur Formation (C); **4a** - Grey limestone and **4b** - Purple shale of Kanger Limestone (K), **5a** - Purple and buff shale and **5b** - Stromatolitic dolomite (Machkot Dolomite Member) of Jagadalpur Formation (J).

## Stratigraphy

The succession is called the Indravati Group after the Indravati River running along the middle of the basin. Basal arkose rests over the eroded surface of granitoid basement, and occurs also as sedimentary Neptunian dykes (infillings in the joints of basement granite) away from the present boundaries of the basin, suggesting its past areal spread. The overlying quartz pebble conglomerate contains rare clasts of granite and Sukma supracrustals like

**Table 5.4.** Stratigraphy of Indravati basin

| | |
|---|---|
| Jagdalpur Formation (200-250 m) | Purple shale with stromatolitic dolomite |
| Kanger Limestone (50-200 m) | Purple limestone and laminated shale |
| Cherakur Formation (50-60 m) | Purple shale and siltstone with interbeds of arkosic sandstone, chert pebble conglomerate and 'grit' |
| Tiratgarh Formation (50-60 m) | Quartz arenite with minor laminated shale, subarkose and quartz pebble conglomerate |
| ----------------Unconformity--------------- | |
| Granites, gneisses and supracrustal enclaves | |

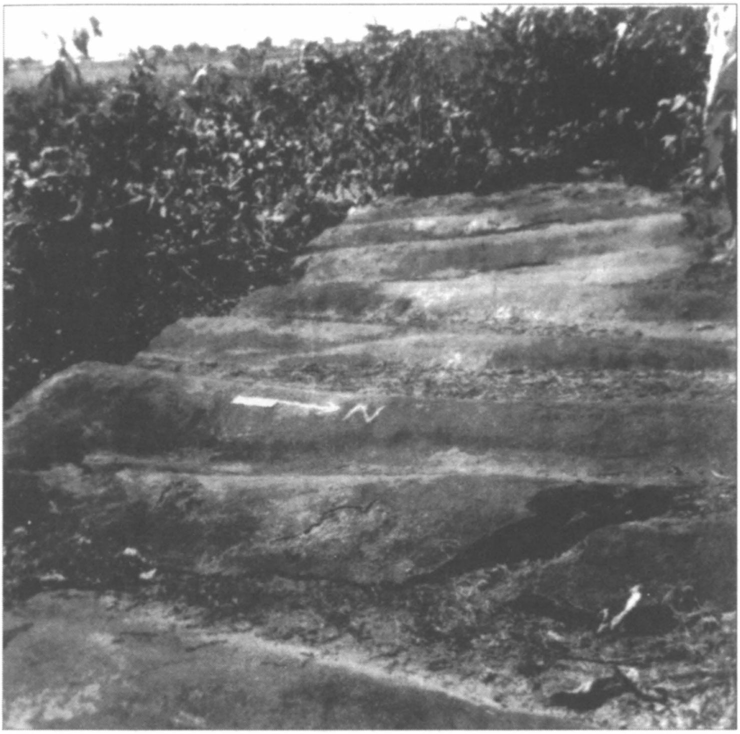

**Fig.5.11.** Megaripples in Tiratgarh sandstone.

quartzite, cordierite-anthophyllite rock and BIF. The main Tiratgarh sandstone is a mature quartz arenite with abundant ripple marks, including mega-ripples (Fig.5.11) and cross bedding. Minor shale intervals are seen near the top. Cherakur Sandstone is a mixed argillaceous to arenaceous interbedded unit containing glauconite. The arenaceous interbeds are quartz-chert pebble conglomerate and 'grit' with well-rounded and spherical pebbles and granules of chert, jasper and quartz. Kanger Limestone has a grey thick-bedded lower unit, followed by grey laminated micrite in the middle and purple limestone, calcareous shale and local flaggy limestone at the top. Jagdalpur Shale is a widespread unit of fissile purple, grey and buff shales. Spectacular pillars and castellated columns of purple and grey stromatolitic dolomite rise from the low, shaly plains. Intraformational shale pebble conglomerate and bedded chert layers are seen. Shallow water sedimentary structures are also fairly common.

The basal conglomerate and quartzite are regarded as products of shallow marine waters transgressing on to the land. The mixed sand-mud facies that followed suggests a near shore to shallow marine environment. This shallow marine environment continued during the deposition of Kanger Limestone. The shale-limestone-dolomite facies of Jagdalpur Formation with widespread stromatolitic structures suggests tidal flat environment. The overall depositional environment is a shallow epeiric sea with strandline, near shore and tidal flat environment in juxtaposition.

### Structure

Indravati Group is essentially a flat sequence with undulating dips. Tight isoclinal folds trending NE with moderate to steep dips (30-70°) are noticed at the faulted and sheared SE margin in the transition zone of the Eastern Ghat mobile belt. The Kanger and Keam Faults bound the southern margin. The E-W trending Sirisiguda Fault is a tilted strike-slip (wrench) fault offsetting the basin in the middle.

## Sabari Basin

A triangular basin of 700 km$^2$ near Sukma is called Sabari basin after the Sabari River that flows in the middle of the basin (Das et al.2001). It was earlier called Sukma basin by Crookshank (1963) and described later by Ramakrishnan (1987). The Sabari basin is separated from the Indravati basin by the Darba-Jhiram ghat occupied by granites and Bengpal Group, and has faulted contact in the north with Indravati basin. *Chedrapal outlier* consisting of basal conglomerate and quartzite with minor shale is an erosional remnant connecting the Indravati and Sabari basins.

Sabari Group consists of a basal conglomerate and thick-bedded orthoquartzite, overlain by a cream to grey coloured limestone, and followed by purple to grey shale. The sediments are nearly horizontally bedded, but for the faulted and sheared eastern margin where the shales pass into sericitic, chloritic and calcareous phyllites, in contact with the marginal zone of the EGMB.

### Correlation of Basins in Bastar Craton

The broad lithostratgraphic correlation of the various Purana basins of Chhattisgarh State, excluding the Palaeoproterozoic Abujhmar basin is given below:

| Chhattisgarh | Khariar | Ampani | Indravati | Sabari |
|---|---|---|---|---|
| Raipur Gp | — | — | Jagdalpur Sh<br>Kanger Lst. | Sabari Gp<br>(Upper) |
| Chandrapur Gp | Pairi Gp | | Cherakur Fm | Sabari Gp |
| | | Ampani Gp | Tiratgarh Sst | (Lower) |
| Singhora Gp | — | — | — | — |

The Chhattisgarh basin contains the lowest unit of Singhora Group, but the Khariar and Ampani basins and other outliers have only the equivalent of Chandrapur Group/Tiratgarh Sandstone. The Indravati and Sabari basins expose the top calcareous facies that is equivalent of Raipur Group, besides the lower arenaceous facies (Chandrapur Group). The outliers of Keskal, Singanpur and Chendrapal expose the lower part of the succession consisting of basal conglomerate, sandstone and minor shale. The presence of sedimentary dykes of basal arkose as joint fillings in the granitic basement away from the present outcrops of the basin and the distribution of outliers close to larger basins suggest that the basins were once covered by the Purana epeiric sea, probably having interlinking arms between the basins.

### Pranhita-Godavari Basin

Pranhita-Godavari (P-G) basin (Fig.5.12), occurs in two parallel NW-SE trending sub-basins (the western and the eastern), situated at the junction of Dharwar and Bastar cratons, and developed after amalgamation of the cratons in Palaeoproterozoic. The western sub-basin is called the Pakhal belt (or Mallampalli belt) and the eastern sub-basin as the Albaka belt. The P-G basin extends for a length of ~400 km with a width of ~100 km, which includes the width of ~40 km for Godavari graben of Gondwana sediments occurring in the middle and separating the two sub-basins. The aggregate thickness of the sediments of the P-G basin is estimated at about 6000 m. The basin has three prominent outliers on the granitic basement, viz., the Sharnavala outlier linking up with the Cuddapah basin in the south, the Kaddam outlier branching off from the middle of the Pakhal sub-basin at Putnur and Lohara outlier near Chandarpur. There are also three major inliers of the basin within the Gondwana basin viz., Mailaram inlier in the south, Chinnur group of inliers in the middle and Chandarpur inlier in the north. The Pakhal and Albaka belts may have been once continuous and now separated by the Gondwana basin, or formed as two independent basins with different cratonic provenances, the Pakhal belt resting unconformably on the Archaean Dharwar craton and the Albaka belt lying with a tectonic contact on the Bastar craton. The Pakhal belt extends from Khammam in the south to Adilabad in the north and is the better studied of the two. The Albaka belt extends from Bhadrachalam in the south to Chandarpur in the north. Limestone, dolomite and building stones are important resources of the P-G basin, besides minor marble, barite and ironstone.

W. King did pioneering work in the P-G basin in 1881. In 1949, A.M. Heron, and C. Mahadevan provided summaries, which were followed by periodic overviews of stratigraphy and sedimentation by Basumallick (1967), Venkateswara Rao (1977), Subbaraju et al. (1978), Sreenivasa Rao (1987, 1996,

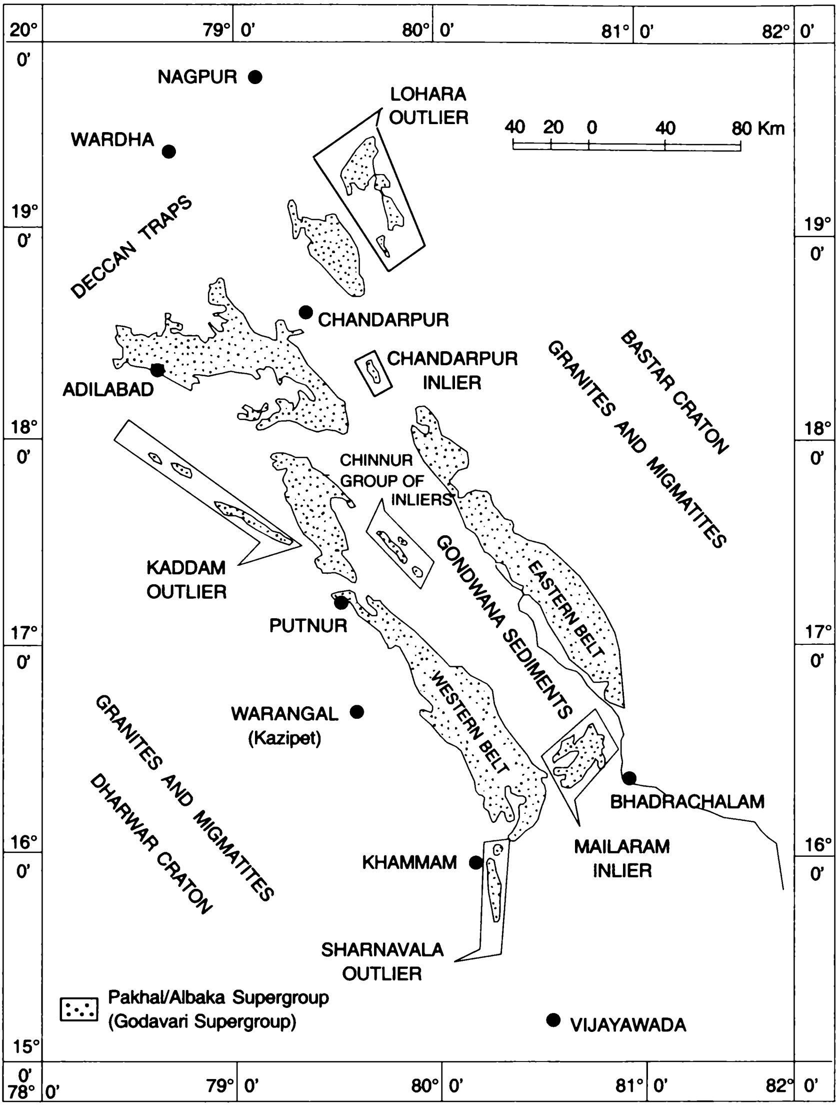
20°
79° 0'
80° 0'
81° 0'
82° 0'
0'
NAGPUR
WARDHA
LOHARA OUTLIER
40 20 0 40 80 Km
19° 0'
DECCAN TRAPS
CHANDARPUR
CHANDARPUR INLIER
ADILABAD
GRANITES AND MIGMATITES
BASTAR CRATON
18° 0'
CHINNUR GROUP OF INLIERS
GONDWANA SEDIMENTS
EASTERN BELT
KADDAM OUTLIER
PUTNUR
17° 0'
WARANGAL (Kazipet)
WESTERN BELT
GRANITES AND MIGMATITES
DHARWAR CRATON
BHADRACHALAM
MAILARAM INLIER
16° 0'
KHAMMAM
SHARNAVALA OUTLIER
Pakhal/Albaka Supergroup (Godavari Supergroup)
VIJAYAWADA
15° 0'
78° 0'
79° 0'
80° 0'
81° 0'
82° 0'

**Fig.5.12.** Generalised map of Pranhita-Godavari basin (after Sreenivasa Rao, 1987).

2001), Srinivasa Rao (1987), Chaudhuri and Chanda (1991), Chakraborty et al. (1996), Saha and Ghosh (1998), Chaudhuri (2003), Sengupta et al. (2003) and Chaudhuri and Deb (2004). The stratigraphic sequence compiled from these sources is given in Table 5.5.

The sediments of Pranhita-Godavari (P-G) basin, called the Godavari Supergroup by Chaudhuri (2003), are divided into four major groups, namely Mallampalli, Mulug, Penganga and Sullavai, separated by three regional unconformities. The correlation of these groups between the Pakhal and Albaka belts is only tentative because of their complex stratigraphic history.

**Table 5.5.** Stratigraphic sequence of Pakhal and Albaka Supergroups (or Godavari Supergroup)

| | Mallampalli Belt (SW) | | Albaka Belt (NE) |
|---|---|---|---|
| | Gondwana Supergroup<br>(Late Palaeozoic-Mesozoic) | | Gondwana Supergroup<br>(Late Palaeozoic-Mesozoic) |
| | - - -Angular Unconformity - - | | - - - - - Fault - - - - - |
| Sullavai Group (870 m) | Venkatapur Sandstone (50)<br>Mancharial Quartzite (150)<br>Ramagiri Formation (360) | Usur Group (1375 m) | Delam Sandstone (200)<br>Doli Sandstone (975)<br>Nambi Formation (200) |
| | - - Angular unconformity - - | | - - - Disconformity - - - |
| Penganga Group (2700 m) | Sat Nala Shale (200)<br>Chanda Limestone / (300)<br>Putnur Limestone<br>Pranhita Sandstone (25-400)<br>Takalapalli Arkose | (=Penganga Group) (1000 m) | Albaka/Pamanuru (Chelimala) Sandstone with basal Utlapalli Conglomerate |
| | - - - - Disconformity - - - - | | - - - - Disconformity - - - - |
| Mulug Group (2830 m) | Laknavaram Shale (1500)<br>Pattipalli Quartzite (300)<br>Enchencheruvu Dolomite (300)<br>Polaram Shale (500)<br>Jakaram Arkose (230) | Venkatapuram Group (2250 m) | Tippapuram Shale (1340)<br>Somadevara Quartzite (915) |
| | - - - - - Disconformity - - - - | | - - -- Disconformity/Fault - - |
| Mallampalli Group (825 m) | Pandikunta Shale /<br>Karlai Shale (340)<br>Gunjeda Dolomite /<br>Bayyaram Quartzite<br>Bolapalli Formation (185) | | Cherla Formation / Somanpalli Gp |
| | - - -Non-conformity / Angular unconformity - - | | - - - Non conformity / Angular unconformity- - - - |
| | Crystalline basement<br>(Dharwar craton) | | Crystalline basement<br>(Bastar craton) |

Numbers in parenthesis denotes thickness in metres

Some authors therefore prefer to call the succession in Pakhal belt as Pakhal Supergroup and in the Albaka belt as Albaka Supergroup. The sediments of the P-G basin are deposited with a profound unconformity on the Archaean basement and are overlain by the Gondwana sediments with a regional unconformity, and are covered by the Deccan Trap in the northwest. Apart from orthoquartzite-shale-carbonate facies, several horizons of felsic pyroclastics and rare manganiferous chert are noticed in the P-G basin.

## Pakhal (Mallampalli) Belt

### *Mallampalli Group*

The basal Bolapalli Quartzite rests with angular unconformity or non-conformity over the Karimnagar granulite belt and the high-grade supracrustal enclaves of Warangal Group in Dharwar craton. Bolapalli Formation consists of arkose with subordinate conglomerate, glauconitic sandstone, chert breccia, shale, chert and dolomite. Bayyaram Quartzite is a ferruginous quartzite with hematite concentrations and grades into dolomite (Gunjeda Dolomite) interbedded with glauconitic arkose. Pandikunta Shale is a dominant shale unit with stromatolitic dolomite interbeds. Karlai Shale is intercalated with carbonaceous shale, dolomite, siltstone and quartzite. Mallampalli Group with its stromatolitic dolomite, glauconitic arenite as well as halite casts and mudcracks in shale suggests an intertidal environment.

### *Mulug Group*

Mulug Group overlies the Mallampalli Group with a disconformity or a faulted contact. The basal Jakaram Arkose consists of arkose, quartz and chert pebble conglomerate, glauconitic sandstone and shale. Polaram Shale is siliceous and carbonaceous shale with some chert and dolomite. Enchencheruvu Dolomite is a shaly and flaggy dolomite intercalated with calcareous shale and chert. Pattipalli Quartzite is a laterally impersistent coarse-grained quartz arenite with some ferruginous quartzite and local pebble beds. Laknavaram Shale is carbonaceous shale with dolomite and arenite interbeds. The carbonaceous shale-dolomite association of Mulug Group suggests a lagoonal to tidal flat environment, with the arenites forming offshore bars.

### *Penganga Group*

Penganga Group is in fault contact with the basement granite as well as Mallampalli Group. In the Penganga basin, the succession starts with the basal Takalapalli Arkose that overlies the basement granite gneiss non-conformably. Takalapalli Arkose consists of coarse-grained arkose with quartzite interbeds. The partly argillaceous Putnur Limestone overlies the arkose. In Adilabad area, Penganga Group unconformably overlies Pandikunta Shale of Mallampalli Group and consists of Pranhita Sandstone, Chanda Limestone and Sat Nala Shale. Pranhita Sandstone consists of pebbly red arkose, conglomerate and shaly sandstone. The overlying Chanda Limestone (Fig.5.13a) is mainly a shaly limestone with interbeds of shale and manganiferous chert, locally enclosing angular granite clasts near the contact with the basement. The overlying

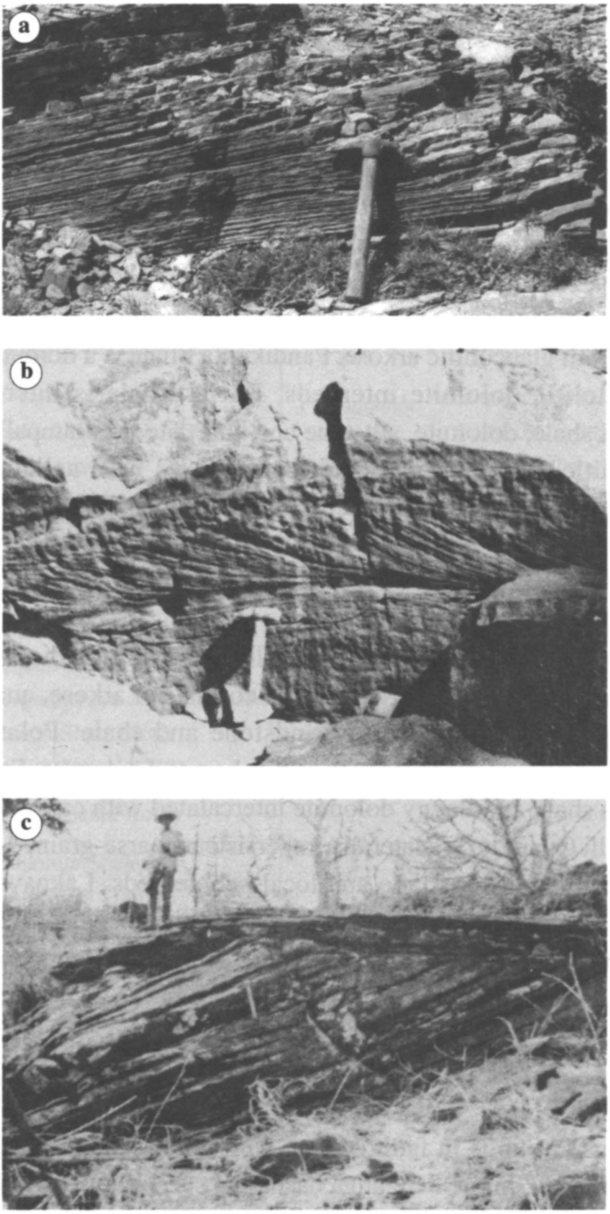

**Fig.5.13.** (**a**) Thin bedded Chanda Limestone, Penganga Group (Soman and Kale, 1990), (**b**)Tabular tangential type cross-bedding in Albaka (Pamanuru) Sandstone (Srinivasa Rao, 1987), (**c**) Large scale cross-bedding in Doli Sandstone, Usur Group (Srinivasa Rao, 1987).

Sat Nala Shale is purple shale devoid of sand. Penganga Group commenced as a coastal alluvial fan to shallow shelf, proceeded to shoreface and muddy shelf onto a carbonate platform culminating in deep water mud deposit, representing deep epicratonic sea joining an open sea.

### *Sullavai Group*

Sullavai Group, named after Chelvai village, overlies Mulug Group with angular unconformity on Laknavaram Shale near Laknavaram Lake and Ramagundam. It also overlies Penganga Group with angular unconformity and the basement granite non-conformably. Sullavai Group consists predominantly of overlapping arenaceous units that are divided into a number of formations (*see* Table 5.5). Due to stratigraphic uncertainty and frequent overlaps, units like Encharani Quartzite, Kapra Sandstone and Venampalli Sandstone are excluded from the table. The basal conglomerate contains boulders and pebbles of vein quartz and quartzite. The conglomerate is associated with glauconitic quartz arenite. Red and white banding and spotted appearance are characteristic of the overlying sandstone. They are also seen in the outliers and inliers of the basin. The sandstone is sheet-like, arkosic and quartzose representing deposits of streams and aeolian sand seas.

## Albaka Belt

The rock formations of Albaka belt are broadly correlatable with those of Pakhal belt. The lower Somanpalli Group is correlated with Mallampalli Group, but in view of numerous faults traversing the sequence, the division into formations is beset with difficulty. Sreenivasa Rao (1987) proposed the name of Cherla Formation for the basal unit of quartzite, arkose, cherty dolomite, limestone and shale. The contact of Cherla Formation with the underlying granite is either non-conformable or faulted. Saha and Ghosh (1998) designated these rocks as Somanpalli Group that was divided into many formations whose inter-relations are unclear. According to these authors, Somanpalli Group consists of arkosic wacke and quartz arenite at the base, followed by parallel laminated shale, quartz arenite and dolomite-chert sequence and chert breccia. The lithological ensemble suggests that the near shore to offshore environment evidenced by laminated shale gave place to tidal flat zone represented by chert-dolomite association. Disconformity or fault separates Cherla Formation/ Somanpalli Group from the overlying Venkatapuram Group that is correlated with Mulug Group and consists of Somadevara Quartzite and Tippapuram Shale. Reworked clasts of Somanpalli Group in the basal Somadevara Quartzite indicates a disconformity. Somadevara Quartzite consists of coarse-grained quartzite with basal pebbly layers, and Tippapuram Shale is made of massive silty shale with interbeds of dolomite, chert, shale pebble conglomerate and quartzite. The environment visualised for Venkatapuram Group is shallow shelf, offshore and tidal ridge. Venkatapuram Group is disconformably overlain by the Albaka or Pamanuru Sandstone (Fig.5.13b) containing the basal, matrix-supported Utlapalli Conglomerate and a monotonous thick unit of sandstone with quartz and lithic wacke interbeds. The sandstone is laminated and variegated, containing shallow water sedimentary structures. Albaka Sandstone has no correlatives in the Pakhal belt, but probably spans the broad time interval represented by Penganga Group. Albaka Sandstone is disconformably overlain by Usur Group that is equivalent of Sullavai Group. The disconformity between Albaka Sandstone and the Usur Group is tectonically and temporally significant. Usur Group consists of Nambi Breccia, Doli Sandstone (Fig.5.13c) and Delam Sandstone. The presence of basal beds of boulder conglomerate and pebbly sandstone (Nambi Breccia) indicates that they are debris flows typical of alluvial fans. The overlying profusely cross-bedded sandstone and pebble conglomerate (Doli Sandstone) represent channel bar to channel lag deposit. The top reddish brown felspathic siltstone (Delam Sandstone) is a flood plain deposit. The overall environment of Usur Group is that of an alluvial fan.

### Structure of P-G Basin

The sediments of the P-G basin strike NW-SE with moderate dips towards NE. Deformational structures in the basin are pre-Sullavai, since the Sullavai Group is deposited over the folded pre-Sullavai succession with angular unconformity. The northern part of Pakhal belt is made of thrust sheets inferred from stratigraphy and facies change. There are also asymmetric SW-verging folds related to the thrusts. The movement on the thrusts is top-to-SW. In the central part of the belt, the sediments are deformed into a fold-fault belt. Doubly plunging folds are seen in the Kaddam outlier that is bounded by faults at the margins. Along the southern margin in the Yellandlapad area and Mailaram inlier, the sediments are folded into open to tight synclines and anticlines. Imbricate thrusts are also reported. In the region close to the Eastern Ghats mobile belt, map-scale synclines have curved axes swinging from NW to NE parallel to the mobile belt margin. The associated thrusts have top-to-NW sense of movement. In the Albaka belt, Somanpalli Group is affected by NW-trending large folds, shear zones and imbricated thrusts and E-W trending strike-slip faults. The Usur Group is tightly co-folded with the underlying Venkatapuram Group, probably during post-Sullavai (post-Usur times).

Metamorphism also increases in intensity from NW to SE, marked by conversion of shales into slates and phyllites containing chloritoid, andalusite, garnet, staurolite and kyanite in marginal zones. Dolomite is recrystallised into marbles with talc, tremolite, actinolite and diopside. Pyrite is transformed into pyrrhotite (Ramamohana Rao, 1970). There is of course the problem of separating these metamorphosed sediments from the Khammam schists occurring in the vicinity. The increase in metamorphism and deformation is towards the marginal zone of EGMB in the southeast, similar to the situation in the other Purana basins. There is another opinion that increase in metamorphic grade is related to the intrusion of Chimalpahad anorthosite located in the vicinity.

## Age

K- Ar ages of glauconite from the lower parts of the sequence are ~1200-1330 Ma and the middle part ~1150-1300 Ma. The upper parts of the succession yield Rb-Sr mineral ages of ~800-870 Ma. In view of the possible argon loss and authigenic origin of glauconite, a reasonable age estimate, in conformity with the age of neighbouring Purana basins, may be 1000-1600 Ma.

## Tectonics and Basin Evolution

Pranhita-Godavari basin occurs as two parallel linear belts that resemble a rift (*see* Sreenivasa Rao, 1996). Erosional unconformity in the west, occurrence as outliers within the granitic basement in the middle of the basin, and the curved basin boundary linking with the Cuddapah basin through Sharnavala outlier are evidences favouring a cratonic sag basin rather than a rift. Local events of rifting are evidenced by the presence of felsic tuffs and ignimbrites in the stratigraphic sequence. Superposition of Gondwana graben and the associated parallel faults have given the P-G basin a belt-like geometry. The

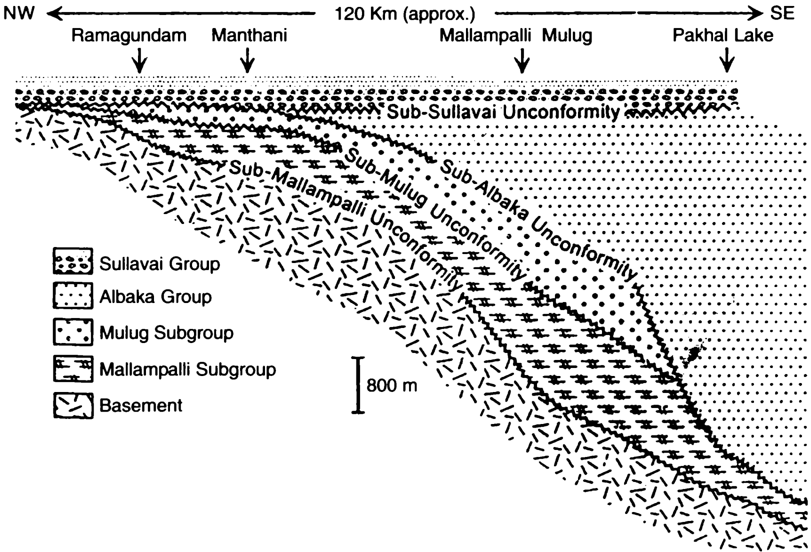
NW
120 Km (approx.)
SE
Ramagundam
Manthani
Mallampalli
Mulug
Pakhal Lake
Sub-Sullavai Unconformity
Sub-Mallampalli Unconformity
Sub-Mulug Unconformity
Sub-Albaka Unconformity
Sullavai Group
Albaka Group
Mulug Subgroup
Mallampalli Subgroup
Basement
800 m

**Fig.5.14.** Correlation of regional unconformities in P-G basin (after Chaudhuri and Deb, 2004, with permission from Elsevier).

faulting probably carried the Pakhal sediments to moderate depths over which Gondwana sediments were later deposited. This has caused disruption in the stratigraphy of P-G basin leading to serious problems of correlation of the eastern and western belts. The main deformation has not significantly affected the younger Sullavai Sandstone in the same way as has happened to younger sediments like Bhander Group in the Vindhyan basin, Kurnool Group in Cuddapah Basin and Badami Group in Kaladgi basin. Stratigraphic and sedimentological studies of the unconformity-bounded successions in the P-G basin (Fig.5.14) indicate that there was southeasterly sloping embayment acting as a pathway for marine transgression from the east.

### Cuddapah Basin

The crescent shaped, easterly concave and N-S trending Cuddapah basin (Fig.5.15a and b) covers an area of 44000 km$^2$ in the east-central part of Dharwar craton. The basin extends for a length of about 450 km along the arcuate eastern margin with a mean width of 150 km, and is the second largest Purana basin of Peninsular India, after the great Vindhyan basin. The arcuate north, south and western boundary of the Cuddapah basin marks the profound unconformity (called Eparchaean Unconformity in early literature) on basement granites enclosing the Eastern greenstone belts of Kadiri, Veligallu and Tsundupalle in the south, and Raichur, Gadwal and Peddavuru in the north. The arcuate eastern margin is marked by a prominent boundary thrust, which is parallel to the Nellore schist belt, Eastern Ghats mobile belt and the East Coast. A giant basic dyke swarm underlies the basin in the west from Chittoor in the south to Mahbubnagar in the north.

Cuddapah basin is characterised by quartzite-carbonate-shale cycles having an aggregate thickness that is estimated to vary between 6 and 12 km. The early sediments of the basin are interspersed with basic volcanics and sills, similar to the small Palaeoproterozoic basins of Abujhmar, Bijawar and Gwalior. Felsic volcanics and tuffs are intercalated with sediments at many horizons. The basin is well known for its mineral potential in the form of limestones and dolomites, bedded and vein barytes, chrysotile asbestos and steatite, besides occurrences of base metals, diamond, phosphorite, uranium and abundant building and ornamental stones.

The western half of the basin is undeformed and consists of four sub-basins, the Papaghni, Kurnool, Srisailam and Palnad. The Papaghni and Kurnool sub-basins are geographically interlinked, but were sites of deposition at different times, the Papaghni sub-basin containing lower Cuddapah sediments, and the Kurnool sub-basin containing the younger Kurnool sediments that overlie the Cuddapah sequence with a major unconformity. Srisailam sub-basin

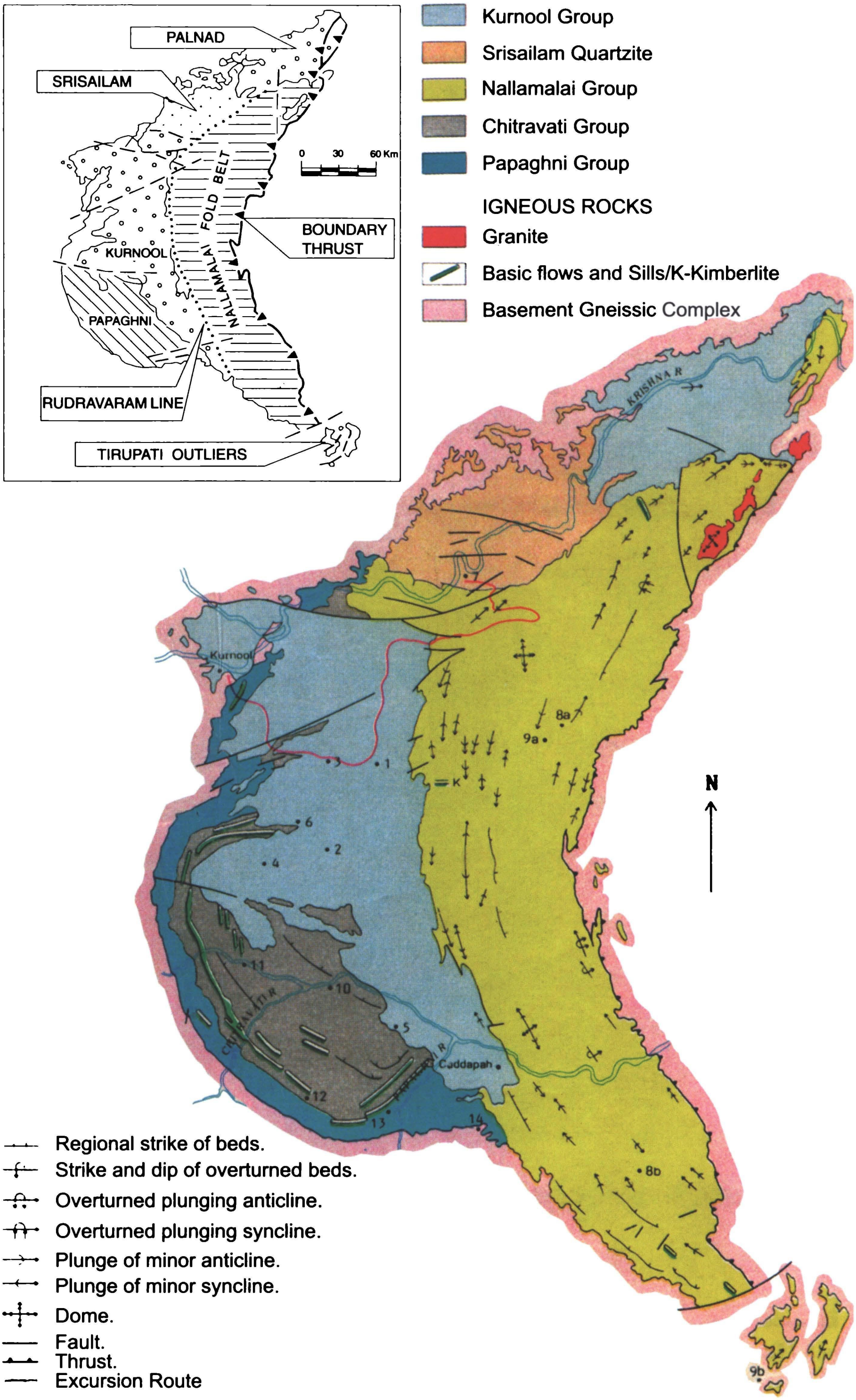
PALNAD
SRISAILAM
KURNOOL
PAPAGHNI
NALLAMALAI FOLD BELT
BOUNDARY THRUST
RUDRAVARAM LINE
TIRUPATI OUTLIERS
0 30 60 Km
Kurnool Group
Srisailam Quartzite
Nallamalai Group
Chitravati Group
Papaghni Group
IGNEOUS ROCKS
Granite
Basic flows and Sills/K-Kimberlite
Basement Gneissic Complex
KRISHNA R
Kurnool
Cuddapah
CHITRAVATI R
PAPAGHNI R
N
K
1
2
3
4
5
6
7
8a
8b
9a
9b
10
11
12
13
14
Regional strike of beds.
Strike and dip of overturned beds.
Overturned plunging anticline.
Overturned plunging syncline.
Plunge of minor anticline.
Plunge of minor syncline.
Dome.
Fault.
Thrust.
Excursion Route

**Fig.5.15a.** Cuddapah basin in Eastern Dharwar craton. *Inset* depicts the different sub-basins (GSI, 1981b).

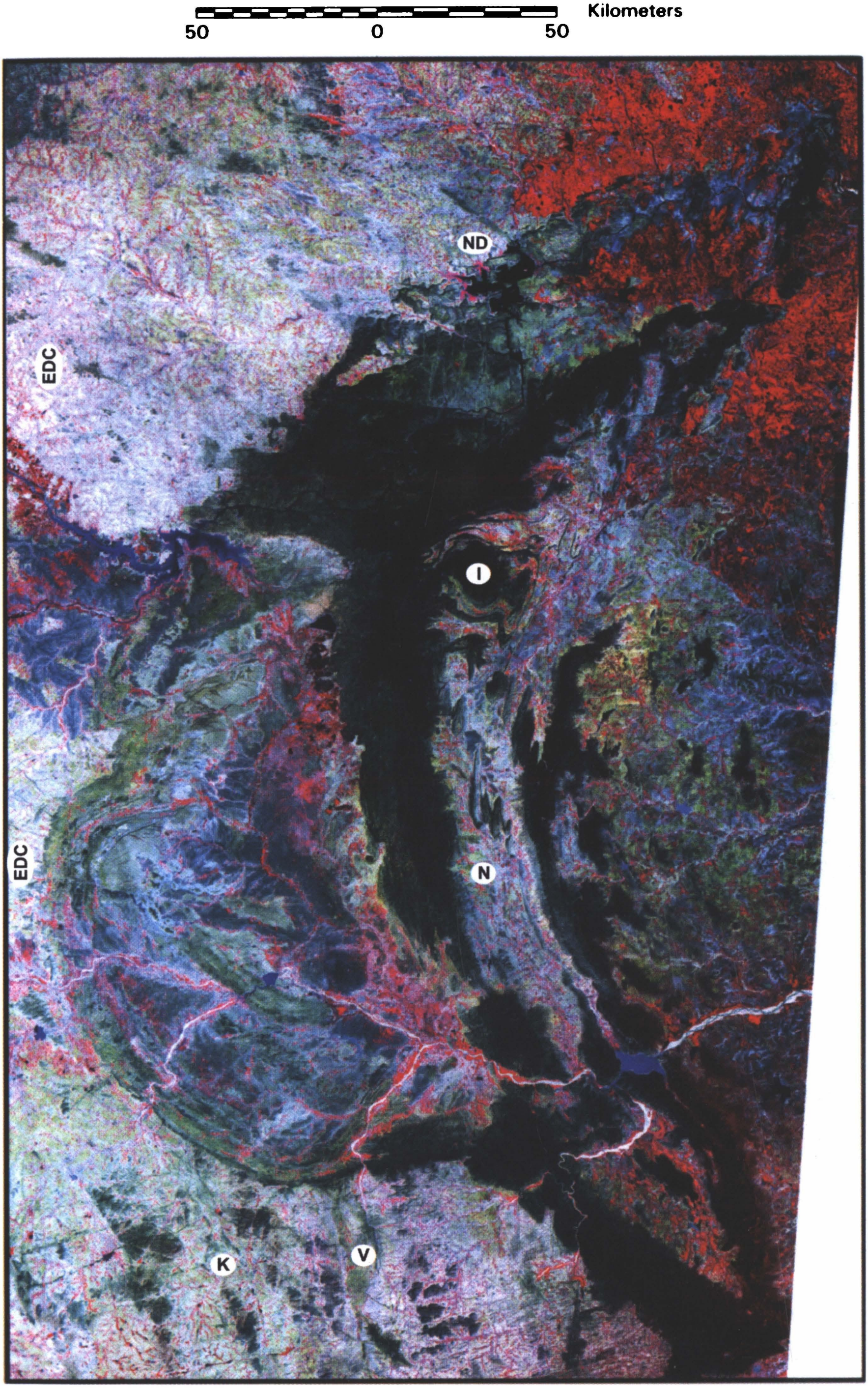

**Fig.5.15b.** Imagery of Cuddapah basin. The arcuate western boundary of the basin overlies Archaean granites of EDC, along with Kadiri (K) and Veligallu (V) greenstone belts. Nallamalai fold belt (N) is prominently seen in the east with Iswarakuppam dome (I). Nagarjuna Sagar Dam (ND) (Courtesy: Geol. Surv. India).

contains upper Cuddapah sediments and Palnad sub-basin exposes only the younger Kurnool sequence. The eastern half of the Cuddapah basin is occupied by the Nallamalai fold belt consisting of upper Cuddapah sediments. Nallamalai fold belt is demarcated from the undeformed western sub-basins by the prominent fault lineament called the Rudravaram Line along which cleavage begins to develop in the Cuddapah sediments, which were intensely deformed towards the boundary thrust in the east.

## Previous Studies

Pioneering work was done in the basin in the eighteen seventies by V. Ball, T. Oldham, R. Bruce Foote and W. King. The monumental work of King (1872) proposing the first stratigraphic sequence for the basin held sway for nearly a century. Systematic mapping by the Geological Survey of India led to some significant changes in stratigraphy: Dutt (1975) on the Kurnool basin, Sen and Narasimha Rao (1967) and GSI (2001c) on volcanism and palaeogeography, S.V.L.N. Rao et al. (1964), Thyagarajan (1964) and Rajurkar and Ramalingaswamy (1975) on stratigraphy and sedimentation, Narayanaswami (1966a) on tectonics and NGRI (1986) on gravity studies. The erstwhile Indian Institute of Peninsular Geology housed in the National Geophysical Research Institute at Hyderabad published four workshop volumes and two monographs on Cuddapah basin, the main results of which were summarised by Y.G.K. Murthy (1981). Concurrently, the Geological Survey of India released 1:250000 scale map of Cuddapah Basin (1979-80) along with an explanatory brochure (GSI, 1981b), which followed the classification proposed by B.K. Nagaraja Rao and G. Ramalingaswamy in 1976. Periodic summaries of the geology were published from time to time, viz, Meijernik et al. (1984), Dutt (1986), Nagaraja Rao et al. (1987), Hari Narain (1987), Ch. Narasimha Rao (*in* GSI 2001c) and Lakshminarayana et al. (2001). The stratigraphy of the basin as modified by Nagaraja Rao et al. (1987) is given in Table 5.6. Generalised stratigraphic columns for the various units of the basin are given in Fig.5.16.

## Stratigraphy

Description of lithological units and their environmental significance are outlined in the following paragraphs:

### Papaghni Group

Papaghni Group rests with non-conformity on the granitic basement and with profound angular unconformity over the greenstone belts of EDC. The unconformity is marked by prominent basal conglomerate. Papaghni Group

**Table 5.6.** Lithostratigraphy of Cuddapah basin

| | | | | |
|---|---|---|---|---|
| | Kurnool Group (200-450) | Kundair Subgroup (75-150) | Nandyal Shale (50-100) | Shale, partly calcareous |
| | | | Koilkuntla Limestone (15-50) | Siliceous, shaly limestone with quartzite interbeds |
| | | | Paniam Quartzite (10-35) | Massive and pinnacled quartzite, siliceous shale, basal pebble bed |
| | | | Paraconformity | |
| | | Jammalamadugu Subgroup (120-260) | Auk Shale (10-15) | Laminated shale, mostly ochreous with siltstone interbeds |
| | | | Narji Limestone (100-200) | Flaggy grey limestone, glauconitic sandstone interbeds |
| | | | Banganapalle Quartzite (10-50) | Oligomict conglomerate, 'grit', quartzite, shale |
| | | | Unconformity | |
| | (300) | | Srisailam Quartzite (300) | Glauconitic ferruginous quartzite with shale |
| | | | Unconformity | |
| CUDDAPAH SUPERGROUP | Nallamalai Group (3500-6000) | (2000) | Cumbum Formation | Mainly slate and phyllite, chert, dolomite |
| | | | Pullampet Formation | Shale, felsic tuff, barytes, dolomite, quartzite |
| | | | Bairenkonda Quartzite (1500)/ | Quartzite, quartz wacke, shale |
| | | | Nagari Quartzite (4000) | Quartzite, quartz wacke, shale, basal conglomerate |
| | | | Angular unconformity | |
| | Chitravati Group (4900-5000) | | Gandikota Quartzite (300) | Shale-quartzite alternations, glauconitic quartzite interbeds |
| | | | Tadpatri Formation (4600) | Shale, felsic tuff, basic sills and flows, chert, stromatolitic dolomite, quartzite |
| | | | Pulivendla Quartzite (1-75) | Quartzite and conglomerate |
| | Papaghni Group (2100) | | Vempalle Formation (1900) with Kuppalapalle Volcanics | Stromatolitic dolomite, chert, quartzite, basic sills and flows |
| | | | Gulcheru Quartzite (30-210) | Basal conglomerate, arkose, quartzite with shale interbeds |
| | | | Crystalline basement of Dharwar craton | |

*Numbers in parenthesis refer to thickness in metres

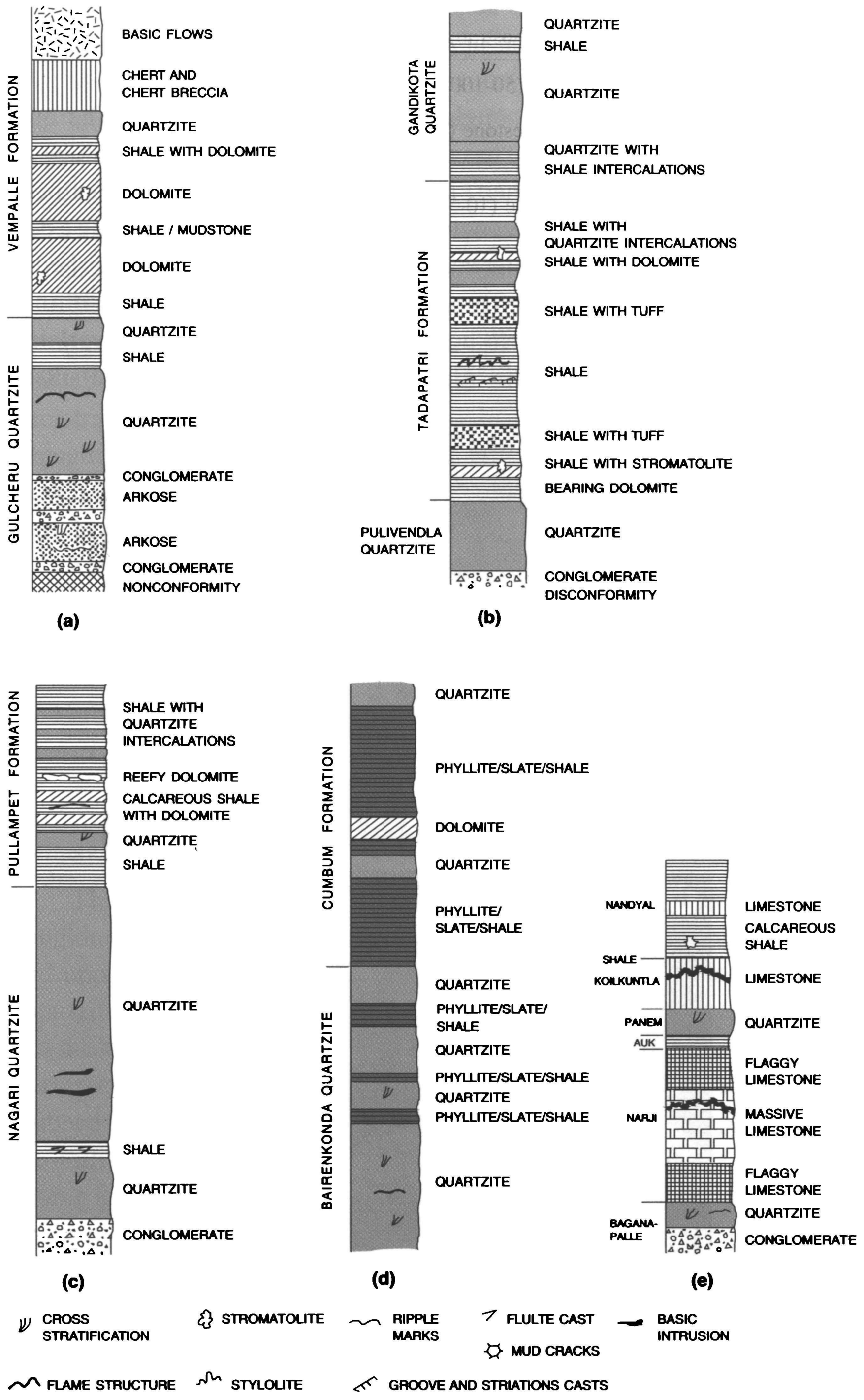
VEMPALLE FORMATION
BASIC FLOWS
CHERT AND CHERT BRECCIA
QUARTZITE
SHALE WITH DOLOMITE
DOLOMITE
SHALE / MUDSTONE
DOLOMITE
SHALE
GULCHERU QUARTZITE
QUARTZITE
SHALE
QUARTZITE
CONGLOMERATE
ARKOSE
ARKOSE
CONGLOMERATE
NONCONFORMITY
(a)
GANDIKOTA QUARTZITE
QUARTZITE
SHALE
QUARTZITE
QUARTZITE WITH SHALE INTERCALATIONS
TADAPATRI FORMATION
SHALE WITH QUARTZITE INTERCALATIONS
SHALE WITH DOLOMITE
SHALE WITH TUFF
SHALE
SHALE WITH TUFF
SHALE WITH STROMATOLITE BEARING DOLOMITE
PULIVENDLA QUARTZITE
QUARTZITE
CONGLOMERATE
DISCONFORMITY
(b)
PULLAMPET FORMATION
SHALE WITH QUARTZITE INTERCALATIONS
REEFY DOLOMITE
CALCAREOUS SHALE WITH DOLOMITE
QUARTZITE
SHALE
NAGARI QUARTZITE
QUARTZITE
SHALE
QUARTZITE
CONGLOMERATE
(c)
CUMBUM FORMATION
QUARTZITE
PHYLLITE/SLATE/SHALE
DOLOMITE
QUARTZITE
PHYLLITE/ SLATE/SHALE
BAIRENKONDA QUARTZITE
QUARTZITE
PHYLLITE/SLATE/ SHALE
QUARTZITE
PHYLLITE/SLATE/SHALE
QUARTZITE
PHYLLITE/SLATE/SHALE
QUARTZITE
(d)
NANDYAL
SHALE
KOILKUNTLA
PANEM
AUK
NARJI
BAGANA-PALLE
LIMESTONE
CALCAREOUS SHALE
LIMESTONE
QUARTZITE
FLAGGY LIMESTONE
MASSIVE LIMESTONE
FLAGGY LIMESTONE
QUARTZITE
CONGLOMERATE
(e)
CROSS STRATIFICATION
STROMATOLITE
RIPPLE MARKS
FLULTE CAST
MUD CRACKS
BASIC INTRUSION
FLAME STRUCTURE
STYLOLITE
GROOVE AND STRIATIONS CASTS

**Fig.5.16.** Generalised startigraphic column of (**a**) Papaghni Group, (**b**) Chitravati Group, (**c** & **d**) Nallamalai Group and (**e**) Kurnool Group (after Nagaraja Rao et al. 1987).

consists of a lower arenaceous sequence (Gulcheru Quartzite, named after Guvvalacheruvu village) and an upper carbonate sequence topped by basic volcanics and sills (Vempalle Formation).

*Gulcheru Quartzite* is a conglomerate-quartzite sequence. The quartz pebble conglomerate (Fig.5.17a) has dominant clasts of vein quartz, along with pebbles of granite, quartzite, chert, jasper and BIF. It consists of both clast-supported and matrix-supported conglomerates, the former representing a debris flow in an alluvial fan and the latter containing scour surfaces and cross bedding indicating a braided river environment. Lenticular quartzite within the conglomerate may suggest storm activity. The conglomerate is overlain by pebbly and non-pebbly quartzite, glauconitic sandstone, laminated siltstone

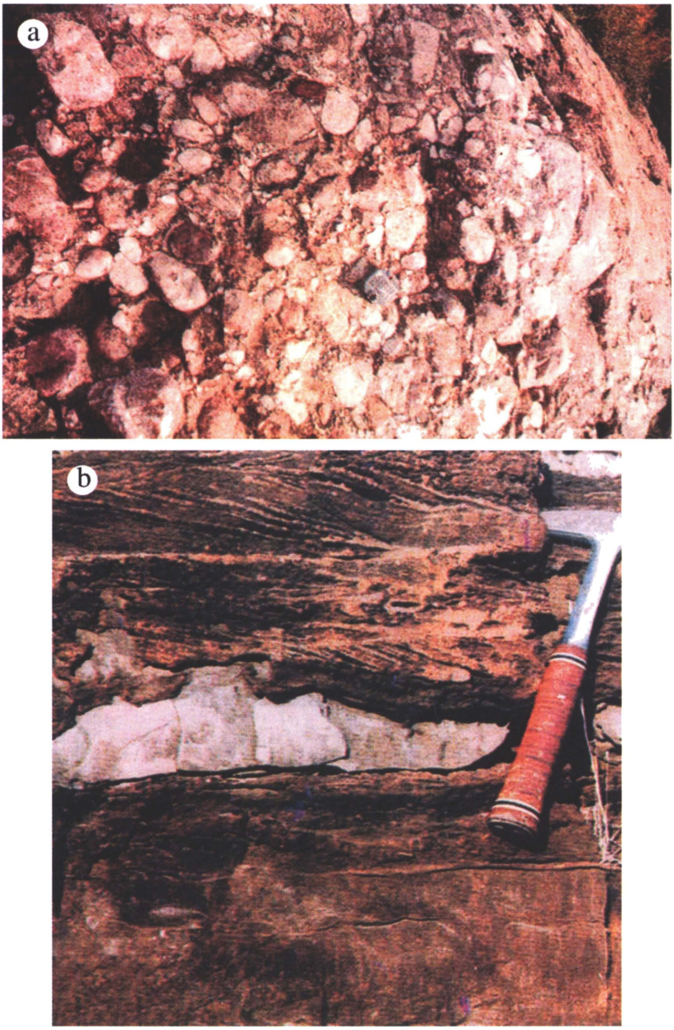

**Fig.5.17.** (**a**) Gulcheru oligomict conglomerate. (**b**) Vempalle dolomite inter-stratified with siliceous oolite (Lakshminarayana et al. 2001).

and shale interlayered with dolomite. Fan delta to shallow marine setting is visualised for this association.

*Vempalle Formation* comprises shale, siltstone, sandstone and stromatolitic dolomite in the lower part, associated with phosphatic and uraniferous horizons. Oolitic dolomite with quartz or carbonate nucleus and concentric iron oxide rings is seen near Dhone (Fig 5.17b). The upper unit consists of shale-chert beds, chert breccia, sandstone and stromatolitic dolomite. The lithological association suggests tidal flat to shallow marine environment.

*Kuppalapalle Volcanics* consisting of tholeiitic basalt and basaltic andesite occur at the top of Vempalle Formation. Sills of picrite, gabbro and dolerite are also abundant. The flows and sills are horizontal or low dipping and are interstratified with sediments. They follow the parallel, arcuate pattern of the Papaghni sub-basin and may represent horizontal fissure eruptions emanating from a large elliptical basic body (lopolith?) occurring at depth, as interpreted from gravity and aeromagnetic data.

Most of the basic lavas are amygdular, with amygdales filled by epidote, quartz, calcite and zeolite (?). They have flow banding and are locally porphyritic, and consist of clinopyroxene, calcic plagioclase and olivine. They may be differentiates from primary picritic magma. The basic sills that intrude the Vempalle dolomite are responsible for deposits of steatite, and of chrysotile asbestos in serpentine, which are produced by contact metasomatism.

### Chitravati Group

This group disconformably overlies Papaghni Group with a basal conglomerate marking the hiatus, and consists of lower Pulivendla Quartzite and upper Tadpatri Formation. They were originally correlated with Nagari Quartzite and Pullampet Formation respectively, but recent studies have shown that the latter two formations are part of Nallamalai Group. Nagari and Pullampet Formations had their type area near Cheyair River and hence were earlier clubbed into *Cheyair Group*. In view of this changed stratigraphic status, with the Pulivendla (Pulivendula) Quartzite and Tadpatri (Tadipatri) Formation having their type areas in Chitravati River section, these formations are included under the Chitravati Group, following Narayanaswami (1966a). Meijernik et al. (1984), who divided the Cuddapah sequence into many subgroups, combined the Pulivendla and Tadpatri Formations into Magamureru Subgroup, but later workers did not follow this terminology.

*Pulivendla Quartzite* consists mainly of basal conglomerate, quartzite and rippled siltstone. Basal conglomerate overlies Vempalle sediments, but quartzite overlies Kuppalapalle Volcanics. The conglomerate has clasts of underlying Papaghni Group. The interpreted environment is alluvial-strandline interface.

*Tadpatri Formation* has a 10 m thick gradational contact with the underlying Pulivendla Quartzite. It consists of purple shale with siltstone and carbonate, and grey shale interbedded with stromatolitic dolomite having biogenic (?) concretions, chert beds and siltstone intercalations. A large thickness of felsic pyroclastics is seen in Tadpatri Formation. The pyroclasts are mainly cherty tuffs, crystal tuffs, ash flows and ignimbrites. Several ridge-like sills of gabbro and dolerite are conspicuous. Pillowed spilitic lava suggestive of submarine alteration is noted at Venkatapuram. The presence of tidalite, as well as flaser- and lenticular bedding suggests tidal flat to shallow offshore environment.

*Gandikota Quartzite* named after the Gandikota Fort has a gradational contact with Tadpatri Formation marked by shale-siltstone-sandstone alternations. The overlying thick quartzite is profusely ripple-marked and cross-laminated. Presence of glauconite, high degree of maturity, sheet geometry and herringbone cross bedding in the quartzite suggests tide-dominated shallow shelf sea setting.

Earlier workers correlated Nagari and Bairenkonda Quartzites with the Gandikota Quartzite. Bairenkonda Quartzite is seen as the strike extension of Nagari Quartzite, with a postulated connection beneath the Kurnool sub-basin. Gandikota Quartzite grades into Tadpatri Formation and follows the curvature of the Papaghni sub-basin, whereas Nagari Quartzite, along with the underlying shale, unconformably overlies both the granitic basement and the Papaghni Group in the south of Cuddapah basin. Therefore Bairenkonda and Nagari Quartzites are included here as part of Nallamalai Group.

## Nallamalai Group

Deformed and feebly metamorphosed shale-siltstone-quartzite-dolomite sequence of the Nallamalai fold belt belongs to Nallamalai Group (named after Nallamalai Hills), which is divided into Bairenkonda Quartzite and Cumbum Formation. Nagari Quartzite and Pullampet Formation are respectively their stratigraphic equivalents.

*Bairenkonda Quartzite*, named after Bairavunikonda or Virannakonda hill, consists essentially of a quartzite-pelite cycle in the lower part and a thick mature quartz arenite in the upper part. Pelite-arenite cycles are best seen in the Iswarakuppam dome, and arenites are exposed between Chelima and Giddalur as well as at Ahobilam, Maidukuru and Velikonda hills. It has been suggested recently that Bairenkonda Quartzite overlies the shaly sequence of Cumbum Formation (Lakshminarayana et al. 2001) in a coarsening upward cycle, like the Tadpatri shale-Gandikota Quartzite sequence. It is shown by others that Bairenkonda Quartzite unconformably overlies Pullampet Formation at Venganamala. Since it is difficult to draw formational boundaries in an interbedded quartzite-shale sequence, more detailed studies are needed to refine the stratigraphy.

*Nagari Quartzite* is a thick-bedded arenite with herringbone cross bedding and is underlain by a conglomerate. About 6 to 10 km thick slate unit underlies the quartzite at the western margin of the basin. Outliers of quartzite at Nagari, Vadamala, Birkuppam and Kalahasti (called Tirupati outliers in the inset map of Fig.5.15a) form picturesque cliffs and tablelands. Nagari Quartzite at the temple town of Tirupati occurs as a natural arch that marks the Eparchaean unconformity, and is declared as a National Geological Monument. Bairenkonda and Nagari Quartzites indicate shallow marine depositional environment.

*Cumbum Formation*, named after Kambham village, is an essentially shaly sequence of banded shale (Fig.5.17c) and shaly rhythmite (Fig.5.17d) that progresses into slate and phyllite associated with arenite, towards the eastern margin of the basin. Chert, dolomite, olistromal dolomite and siliceous shale are locally important. The dolomite hosts a marginal lead-zinc deposit at Agnigundala and Zangamrajupalle-Varikunta. The depositional environment of Cumbum Formation is probably supra-tidal.

*Pullampet Formation*, occurring in the south, consists of purple shale and calcareous shale with interbeds of dolomite and quartzite. The sequence extends along the strike, without any break, into Cumbum Formation in the north. Pullampet Formation probably represents a lagoonal sediment. The single largest deposit of bedded barytes in the world occurs within Pullampet Formation at Mangampeta, where volcaniclastics rich in barite rosettes and barium felspar (celsian) host the deposit. The genesis of this barite deposit is attributed to the reaction between volcanogenic barium and biogenic sulfur in seawater. This unique occurrence has been declared as a National Geological Monument.

*Srisailam Quartzite* is a horizontally bedded, glauconite-bearing ferruginous quartzite overlying Papaghni and Nallamalai Groups with a profound unconformity marked by local conglomerate. Minor shale intercalations are found in the quartzite. *Irlakonda Quartzite* and *Kolamnala Shale*, once thought to be part of Srisailam Quartzite, are now shown to be the equivalents of the Cumbum Formation, since Srisailam Quartzite overlies them with angular unconformity at Madapuchelima. The quartzite is believed to indicate a shallow marine to tidal flat environment.

### Stratigraphic Riddle

The similarity of lithological attributes and sedimentary structures of many lithologic packages in Cuddapah basin has led to the suggestion that the

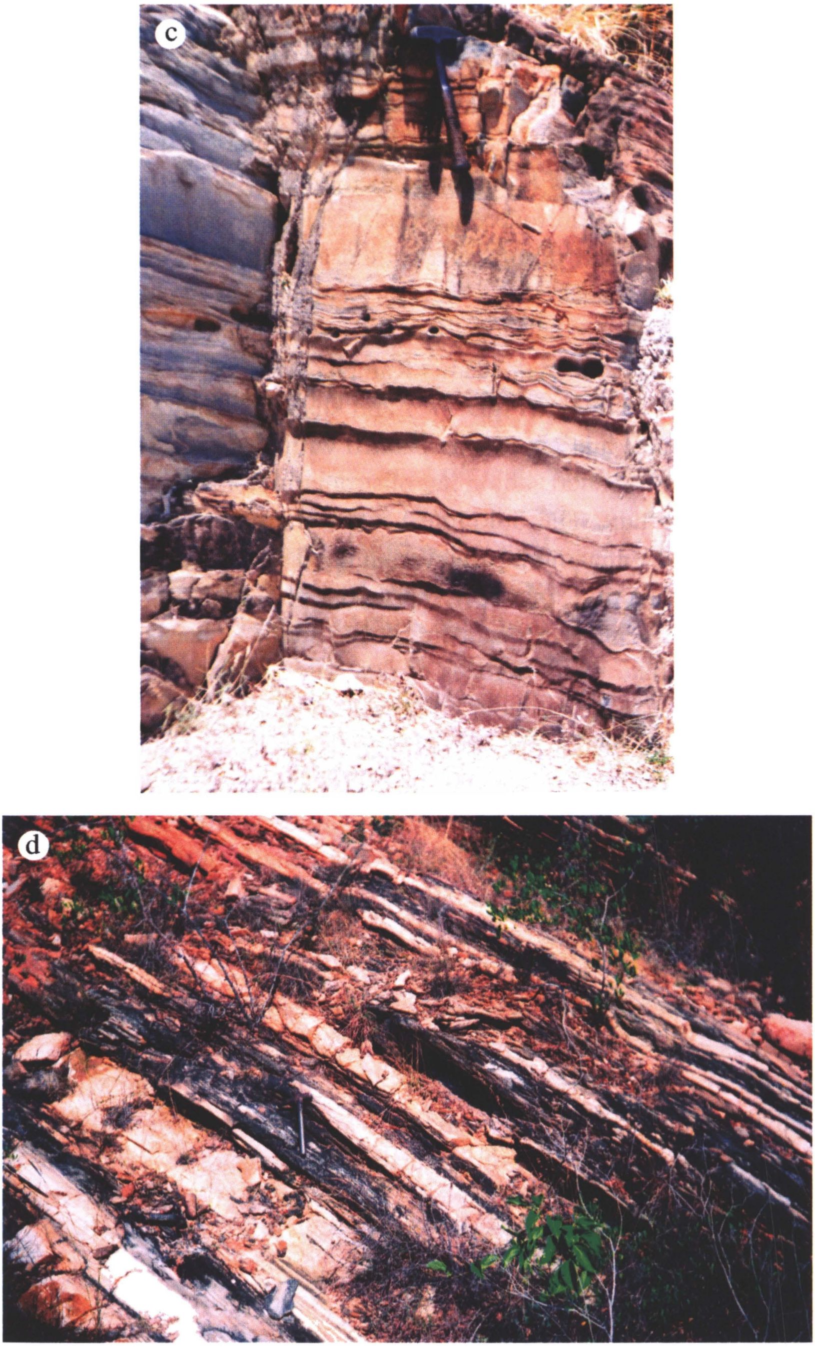

**Fig.5.17.** (**c**) Banded shale, Cumbum Formation. (**d**) Alternate beds of phyllite and quartzite forming shaly rhythmite, Cumbum Formation (after Lakshminarayana et al. 2001).

Tadpatri-Gandikota, Cumbum-Bairenkonda and Nagari-Srisailam quartzites (Fig 5.18a) underlain by shales are the time and facies equivalents deposited in a single sedimentation episode. This would mean that the Cuddapah Supergroup would have only Papaghni and Nallamalai Groups, with the remaining sequences forming part of the Nallamalai Group (Lakshminarayana et al. 2001). A note of caution is needed here because mutual field relations in vast platform basins are difficult to interpret among the frequently repetitive lithologic sequences occurring in discontinuous outcrops (Fig 5.18b), that are either

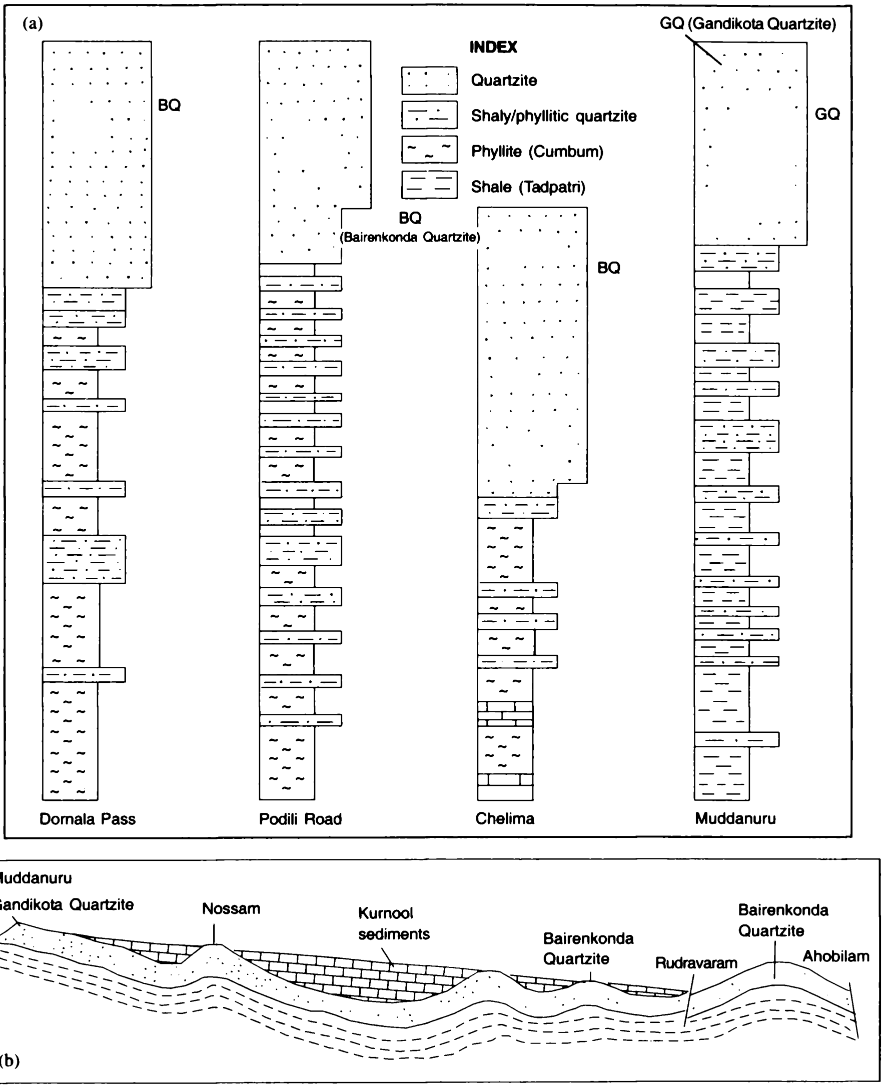
(a)
BQ
INDEX
Quartzite
Shaly/phyllitic quartzite
Phyllite (Cumbum)
Shale (Tadpatri)
BQ
(Bairenkonda Quartzite)
GQ (Gandikota Quartzite)
BQ
GQ
Domala Pass
Podili Road
Chelima
Muddanuru
Muddanuru
Gandikota Quartzite
Nossam
Kurnool sediments
Bairenkonda Quartzite
Rudravaram
Bairenkonda Quartzite
Ahobilam
(b)

**Fig.5.18.** (**a**) Coarsening upward cycles in Cumbum-Bairenkonda and Tadpatri-Gandikota Formations. (**b**) Schematic geological cross section along Muddanur-Nossam-Ahobilam section (not to scale) (after Lakshminarayana et al. 2001).

hidden under a younger sedimentary cover or separated by large faults, or situated in deformed (e.g., Nallamalai) versus undeformed sectors (e.g., Papaghni, Kurnool, Palnad) in different sub-basins. It is therefore important to resolve space-time relationships between similar lithological packages denoting similar depositional environments, but occurring in different parts of a vast basin that is affected by frequent facies changes, having differences in deformational history and disruption by faulting. Detailed geological mapping of critical areas, coupled with modern sedimentological, geochemical and isotopic studies, will be necessary to solve such stratigraphic riddles.

A view has been recently put forward that the low-grade Nellore schists are only more metamorphosed equivalents of Nallamalai sediments as seen in the Velikonda hills up to Podili (Lakshminarayana et al. 2001). Since the high-grade Nellore schists like amphibolites and kyanite-sillimanite schists are in concordant and gradational contact with the low-grade Nellore schists like mica phyllites, sericite-chlorite schists and metabasalts, the parallelism of structural trends alone, in an apparently progressive metamorphic sequence, is not a conclusive evidence for the stratigraphic equivalence of Nallamalai phyllites and low-grade Nellore schists.

### Kurnool Group

Prolonged quiescence after the Cuddapah sedimentation resulted in the emergence of two quartzite-limestone-shale cycles in the Kurnool and Palnad sub-basins (200-450 m) (*see* Table 5.6).

*Banganapalle Conglomerate* contains clasts of chert and vein quartz set in a ferruginous matrix, which is similar to beach gravel formed by transgressive seas. The conglomerate is well known for placer diamonds derived from kimberlites within and around the basin. The associated glauconitic sandstones suggest tidal flat environment. The dark grey micritic *Narji Limestone* indicates restricted circulation, and the intercalated glauconitic sandstone suggests shallow marine conditions. *Auk Shale (Owk Shale)* is siliceous and shows near-shore features.

The overlying *Paniam Quartzite* with high degree of roundness and sphericity and mega cross bedding suggests near shore environment. *Koilkuntla Limestone* is a micritic grey limestone deposited in a shallow marine reducing environment. Purple calcareous shale with interbedded limestone (*Nandyal Shale*) indicates shallow marine conditions. The Kurnool sub-basin therefore witnessed strandline, near shore to shallow marine conditions.

### Structure

The undeformed western sub-basins give way to the highly deformed Nallamalai fold belt in the east. Low amplitude open folds in the west become tight to isoclinal and doubly plunging folds in the east. The folds drape around the basement inliers like Iswarakuppam dome or intrusive granite like Vellaturu (Agnigundala) Granite (1575 Ma). The fold axial traces curve towards south in the Nagari Quartzite (Tirupati outliers), which are displaced to the east along the Karkambadi Fault. Nallamalai fold belt is affected by three phases of deformation (D1 to D3). D1 structures are tight to isoclinal folds; D2 structures include NE trending tight to open folds; and D3 folds trending E-W overprint the earlier structures and are involved in the contractional deformation of Nallamalai and Palnad sub-basins (Saha, 2002). The E-W striking transverse faults of Gani-Kalva ('Kalva Wall') and Atmakur are truncated by the N-S trending fault near Nallamalai hills called the Rudravaram Line. Along the eastern margin thrust, which is confirmed by gravity, magnetic and deep seismic studies, the older Nellore belt and basement granite have overridden the Cuddapah sediments, with a few structural outliers (klippen) scattered near the margin (e.g., near Udayagiri). The folding and thrust faulting are suggested to be post-Kurnool because of the overriding relations of Nallamalai fold belt onto the flat-lying sediments in the western sub-basins. It is likely, however, that the thrusting and folding is multi-episodic, the time sequence being uncertain.

### Geophysics

Deep seismic sounding profiles in the northern part of Cuddapah basin have confirmed the presence of thrust at the eastern boundary. The depth to the basement varied from 1.7 km in Papaghni sub-basin, through 4.5 km in Kurnool sub-basin, to 6.5- 6.8 km in the Nallamalai fold belt. The crustal depth section across the basin (Fig.5.19) shows a four-layer model, with the Moho depth varying between 35 and 39 km (Kaila et al. 1987). An oval-shaped gravity high (+60 mGal) over the Papaghni sub-basin may suggest the presence of a basic magmatic body at depth like a layered intrusion or a meteoritic impact crater.

### Life

Stromatolites abounding in the Cuddapah sediments are not strictly diagnostic of their age. Carbonaceous microfossils like *Tawuia, Chuaria* in Auk Shale, trace fossils in Paniam Quartzite and calcareous algae from Koilkuntla Limestone indicate Neoproterozoic age for the Kurnool Group.

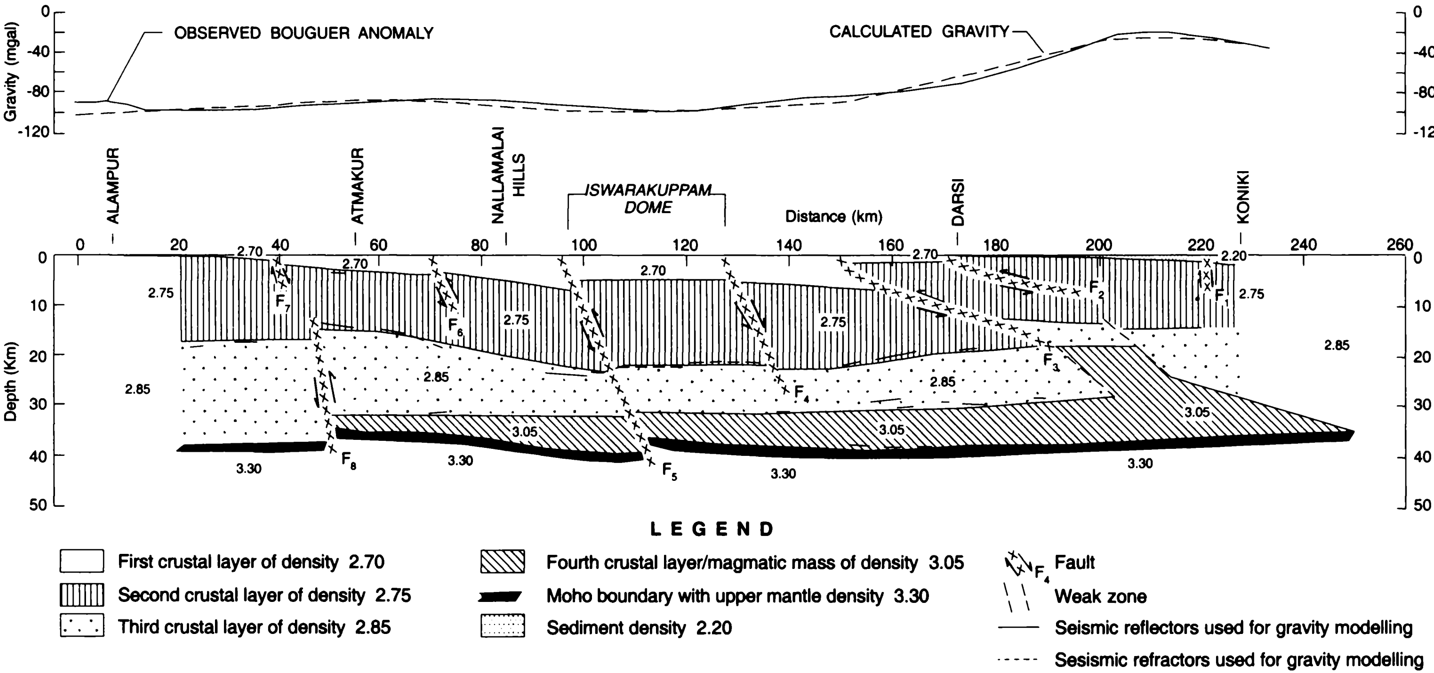
Gravity (mgal)
0
-40
-80
-120
OBSERVED BOUGUER ANOMALY
CALCULATED GRAVITY
ALAMPUR
ATMAKUR
NALLAMALAI HILLS
ISWARAKUPPAM DOME
Distance (km)
DARSI
KONIKI
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Depth (Km)
0
10
20
30
40
50
2.70
2.75
2.85
3.05
3.30
2.20
F1
F2
F3
F4
F5
F6
F7
F8
LEGEND
First crustal layer of density 2.70
Second crustal layer of density 2.75
Third crustal layer of density 2.85
Fourth crustal layer/magmatic mass of density 3.05
Moho boundary with upper mantle density 3.30
Sediment density 2.20
F4 Fault
Weak zone
Seismic reflectors used for gravity modelling
Sesismic refractors used for gravity modelling

**Fig.5.19.** Section along DSS profile in northern Cuddapah basin (modified from Kaila et al. 1987).

### Age

Pre-Cuddapah basement dykes are of two prominent ages at ~2100 and ~2400 Ma. Rb-Sr dating of dolerite and picrite sills of Pulivendla Formation gives an age of ~1800 Ma. K-Ar ages of some dolerite dykes underlying the Cuddapah basin are also similar at ~1800 Ma indicating later thermal impress. These dates also correspond to the age of U mineralisation in lower Cuddapah carbonates at ~1800 Ma. Vellaturu granite from the eastern margin of the basin gives Rb-Sr age of ~1575 Ma, and Vinukonda granite in the vicinity at ~1615 Ma, suggesting an intrusive granitic event at ~1600 Ma. Some dolerite dykes of ~1650 Ma age belong to this event. The ages of galena and micas in Cumbum shales (1350 to 1450 Ma), Mangampeta felsic tuff (1470 Ma) and Chelima lamproite (1350 Ma) suggest thermal events in the basin around 1350-1450 Ma. Younger events recorded by mineral ages range from 500 to 950 Ma, which may span the time of evolution of Eastern Ghats mobile belt. Kimberlites in the granitic basement near the Cuddapah basin generally have an age of ~1050 Ma. Diamondiferous conglomerate having kimberlite as its source for diamond, and Rb-Sr age of ~980 Ma for dolerite dyke intruding Kurnool sub-basin suggests Mesoproterozoic age for Kurnool Group. In summary, the Palaeoproterozoic age for the Papaghni Sub-basin, and Mesoproterozoic age of the rest of the Cuddapah-Kurnool succession are comparable with the chronology of Bijawar-Gwalior and Vindhyan successions surrounding the Bundelkhand craton.

### Tectonics and Basin Evolution

Thermal doming of the asthenosphere caused the crustal upwarp leading to brittle fracturing marked by the profusion of basic dyke swarms (~2100 Ma) close to the site of the Cuddapah basin. The thermal relaxation that followed resulted in downsagging and initiation of the basin. Papaghni sedimentation ensued, together with the associated basic volcanism (~ 1800 Ma) that may be related to the sub-surface basic body in the Papaghni sub-basin. Readjustment and instability initiated horst and graben structures that formed the different sub-basins. Palaeocurrent studies indicate flow direction towards the east during the Papaghni time and to the north during the Chitravati time, suggesting the denudation of Dharwar craton. This is also borne out by the heavy mineral suite of tourmaline and zircon derived from the basement granites as seen in Gulcheru, Pulivendla and Paniam Quartzites. The environment of deposition during Papaghni and Chitravati times was an overall littoral zone, ranging from alluvial fan, coastal plain to tidal flat (Fig.5.20a,b). Sedimentation continued with periodic time gaps. The basin deepened to the east along with sediment

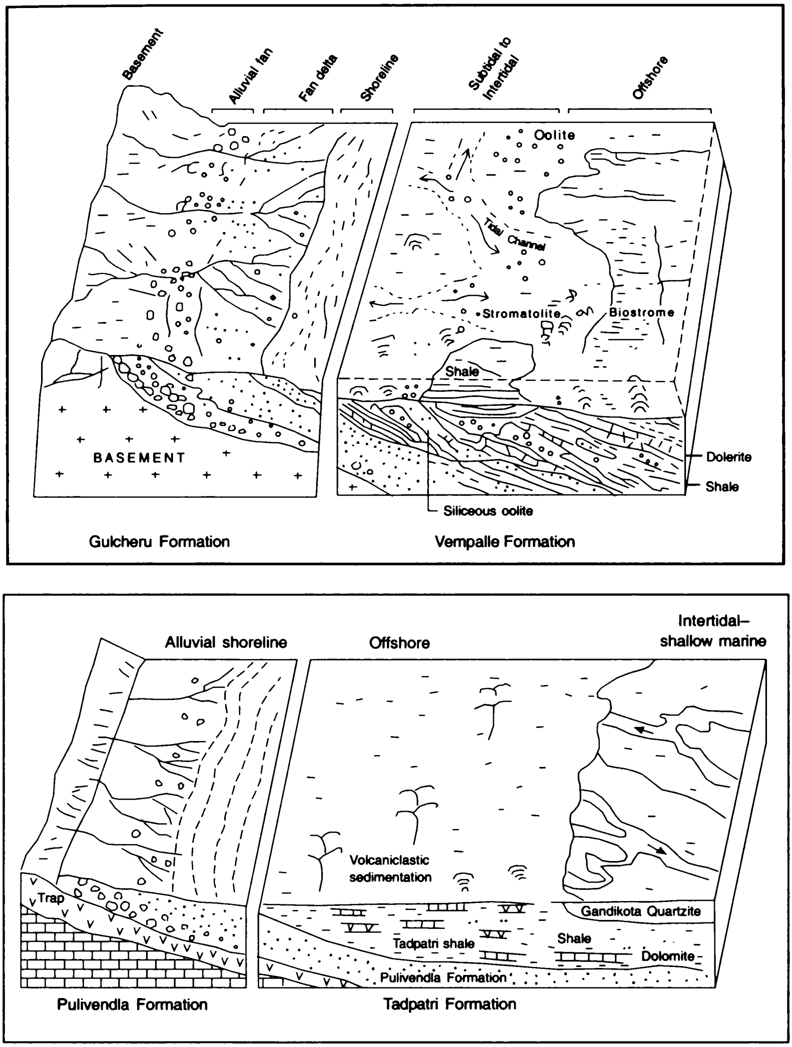
Basement
Alluvial fan
Fan delta
Shoreline
Subtidal to Intertidal
Offshore
Oolite
Tidal Channel
Stromatolite
Biostrome
Shale
BASEMENT
Dolerite
Shale
Siliceous oolite
Gulcheru Formation
Vempalle Formation
Alluvial shoreline
Offshore
Intertidal–shallow marine
Volcaniclastic sedimentation
Trap
Gandikota Quartzite
Tadpatri shale
Shale
Dolomite
Pulivendla Formation
Pulivendla Formation
Tadpatri Formation

**Fig.5.20.** Block diagram showing major sedimentary environments during (**a**) Papaghni episode. (**b**) Chitravati episode (after Lakshminarayana et al. 2001).

thickening, turbidite deposition and felsic volcanism in the deep waters of slope-to-basin setting during Nallamalai times. The younger Kurnool sediments indicate westerly palaeocurrents, and heavy mineral suite of garnet, rutile and ilmenite derived from the terrain to the east. The deformational events associated with Nellore schist belt and Eastern Ghats orogeny caused the thrusting of the basement over the Nallamalai sediments along the prominent boundary thrust (*see* Fig. 5.19). Possible klippen of Nallamalai rocks are seen to the east of the thrust near Udayagiri. Periodic movements created transverse faults and caused the reactivation of the thrust, affecting even the younger Kurnool Group. The Cuddapah basin thus presents a fascinating geological history in Palaeo to Mesoproterozoic, following the cratonisation of Archaean crust in Dharwar craton.

### Kaladgi Basin

Kaladgi basin (Fig 5.21) is an E-W trending irregular basin underlain by the basement granitoids (Peninsular Gneiss and Dharwar Batholith) of the Dharwar craton in the south and east and overlain by the Deccan Trap in the north. The basin covers an area of 8300 km$^2$ and is made of an older Kaladgi sequence and younger Badami sequence occurring in separate sub-basinal areas, like the older Cuddapah and younger Kurnool sequences in Cuddapah basin. Unlike the other Purana basins, Kaladgi basin is not marginally deformed, as it is not spatially associated either with mobile belt or with terrane boundaries.

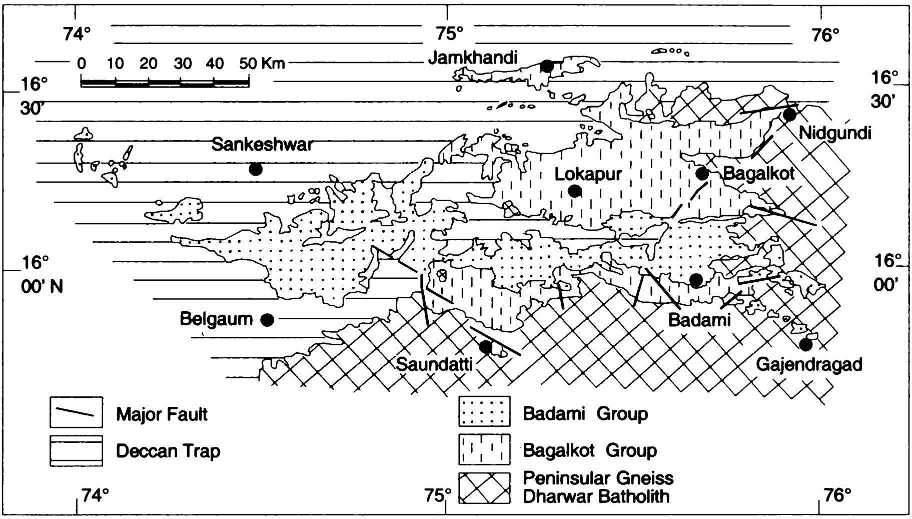
74°
75°
76°
0 10 20 30 40 50 Km
Jamkhandi
16° 30'
16° 30'
Sankeshwar
Nidgundi
Lokapur
Bagalkot
16° 00' N
16° 00'
Belgaum
Badami
Saundatti
Gajendragad
Major Fault
Deccan Trap
Badami Group
Bagalkot Group
Peninsular Gneiss Dharwar Batholith
74°
75°
76°

**Fig.5.21.** Kaladgi basin in Dharwar craton (simplified from Jayaprakash et al. 1987).

Instead, the deformation is concentrated in the centre of the basin with the periphery remaining unaffected. The basin consists of three quartzite-shale-limestone cycles with an aggregate thickness of 4500 m. Kaladgi basin hosts vast resources of limestone and dolomite, as well as building and ornamental stones, besides minor iron ore.

Bruce Foote (1876) systematically mapped the basin and divided the sediments into Lower and Upper Kaladgi 'Series.' M.N. Viswanathiah in 1968 found that the 'sandstone and shale' unit of the Lower Kaladgi 'Series' was a flat-lying unit laid with a marked angular unconformity on the underlying, folded Kaladgi sediments. He therefore proposed (Viswanathiah, 1979) that the lower sequence be called the Kaladgi and the upper the Badami, which was followed by Chandrasekhara Gowda (1981) and (GSI Map, 1981). Symposium volumes (Krishnan, 1964; Viswanathiah, 1979) describe various aspects of the Kaladgi basin. Jayaprakash et al (1987) provide a geological overview of the Kaladgi-Badami basin. The stratigraphy of the basin is presented in Table 5.7.

**Table 5.7.** Lithostratigraphy of the Kaladgi basin

| | | | |
|---|---|---|---|
| | Badami Group (285) | Katageri Limestone (150) | Limestone, shale |
| | | Kerur Arenite (135) | Conglomerate, arenite, shale |
| | | - - - - Angular Unconformity - - - - | |
| | Intrusives | Quartz veins, pegmatites, dolerite dykes | |
| BAGALKOT GROUP | Simikeri Subgroup (1150) | Hosakatti Argillite (700) | Argillite |
| | | Arlikatti Dolomite (130) | Dolomite, hematite bed |
| | | Niralkeri Breccia (40) | Chert breccia |
| | | Kundargi Quartzite (280) | Conglomerate, quartzite, argillite |
| | | - - - - Disconformity - - - - | |
| | Lokapur Subgroup (2750) | Yadahalli Argillite (60) | Argillite |
| | | Muddapur Dolomite (565) | Dolomite, limestone, argillite |
| | | Chikshellikeri Limestone (800) | Limestone, shale |
| | | Yargatti Argillite (720) | Argillite, dolomite |
| | | Mahakut Breccia (130) | Chert breccia |
| | | Saundatti Quartzite (475) | Conglomerate, quartzite, shale |
| | | - - - - Nonconformity and Angular Conformity - - - - | |
| | | Gneisses/Granites and Schist Belts of Dharwar craton | |

N.B. Thickness in metres is given in parenthesis

## Description of Lithology

### *Basement*

Banded gneisses (Peninsular Gneiss) and pink granite (Dharwar Batholith) lie unconformably under the basin in the east and south. Granite also occurs as inliers near Murgod, Sirur, Amingarh and other places. Hungund (Kushtagi) schist belt near Bagalkot and inliers of schists near Mulgali underlie the basin with an angular unconformity. The mixed provenance of dominant granitic basement with greenstone belts is reflected in the geochemistry of the basinal sediments.

The older succession of Kaladgi basin is called the *Bagalkot Group* that corresponds to the Cuddapah Supergroup, and the upper succession is called the *Badami Group* that is the possible equivalent of Kurnool Group. Bagalkot Group is divided into the lower Lokapur Subgroup and the upper Simikeri

Subgroup. The lithostratigraphy of the Kaladgi-Badami basin is described below:

## Bagalkot Group

### *Lokapur Subgroup*

The basal Saundatti Quartzite consists of conglomerate and quartzite. Quartz pebble conglomerate with pebbles of vein quartz and quartzite unconformably overlie granites and gneisses, and are well exposed near Salgundi. The conglomerate overlying the schistose rocks contains in addition, pebbles of BIF and chert. Locally, felspars are abundant in the quartzose matrix. The overlying prominent quartz arenite is seen at Saundatti, Bagalkot and Khanapur. Quartz arenite also occurs as outliers near Nargund, and as inliers in Deccan Trap at Jamkhandi. Purple fissile shales overlie the quartz arenite near Manoli. Mahakut Breccia occurs as lenses in shale and consists of pink microcrystalline silica with angular fragments of chert. The overlying thick Yargatti Argillite, best exposed at Muttalgeri, has intercalations of manganiferous shale, hematite beds and limestone. Grey stromatolitic dolomite (Chitrabhanukot dolomite) forms the top portion of Yargatti Argillite. Friable shale overlies the dolomite. The thickest member of the Bagalkot Group is Chikshellikeri Limestone, which is extensively quarried for industrial purposes. The limestone is variegated and grey coloured and is associated with shale. The limestone and shale are intricately folded. Dolomite forms the top of the limestone formation at Naganur. The overlying Muddapur Dolomite consists of a lower marker argillite (at Jallikatti)), a middle grey limestone (at Petlur) and upper grey stromatolitic dolomite with shale interbeds (at Bamanbudhi). Purple to grey Yadahalli Argillite is the top unit of Lokapur Subgroup.

### *Simikeri Subgroup*

After a hiatus marked by the lensoid Bevimatti conglomerate, Simikeri Subgroup of similar, but less extensive, lithological package to Lokapur Subgroup, occurs in the centre of the basin and is exposed in doubly plunging anticlines and synclines. Thick-bedded mature quartzite and purple laminated shale are the main units of Kundargi (Machkundi) Quartzite. Massive and oolitic chert (novaculite) and chert breccia constitute the Niralkeri Breccia. Banded hematite jasper and hematite schist (BIF) constitute a marker horizon underlying the stromatolitic dolomite-chert-limestone-argillite unit (Arlikatti Dolomite). The topmost unit is a thick highly folded argillite (Hosakatti Argillite), that becomes phyllitic at places. It has thin interbeds of hematite and dolomite.

### *Intrusives*

Numerous pegmatite and quartz veins, and a few dolerite dykes intrude the Bagalkot Group.

### Badami Group

It is an essentially horizontal to low-dipping arenaceous succession with minor shale. The basal Kendur conglomerate in Kerur Arenite overlies the basement granitoids and schists, as well as Bagalkot Group with a major angular unconformity. The main red sandstone unit forming flat-topped hills contains the famous Badami cave temples. Sedimentary structures such as ripple marks, cross beds, groove casts, parting lineations and convolute laminations abound in this sandstone. Badami sandstone occurs as outliers in flat-topped hillocks around Gajendragad and Hanumasagar. The sandstone is overlain by olive shale and grey sandstone. The overlying Katageri Limestone consists of a lower chocolate brown laminated shale with thin siltstone and limestone interbeds, overlain by an upper variegated flaggy limestone with shale partings.

### Sedimentary Environment

Bagalkot Group commences with deposition along a transgressive coast, progressively deepening through a tidal flat and shallow shelf, to offshore with abundant carbonates of the platform. Shale, dolomite with chert, BIF and manganiferous horizons in the succession suggest quiet shelf to lagoonal environment. Badami Group is essentially a coastal to shallow shelf deposit. Palaeocurrents indicate northwesterly palaeoflow for Bagalkot Group and southwesterly palaeoflow for Badami Group.

### Structure

Bagalkot Group, occupying the middle of the elongate basin, is characterised by a series of tight to isoclinal, doubly plunging anticlines and synclines with WNW-ESE axial trace, which are locally refolded by N-S trending folds. Concomitant with deformation, the rocks are metamorphosed, with sandstone becoming quartzite, shale becoming phyllite and micritic carbonate becoming microsparite. Badami Group with gentle dips shows large amplitude open folds. Major E-W faults cut across the basin at Sirur, Saundatti and B.N. Jalihal.

### Life

Rocks of Bagalkot Group are reported to contain algal mats and acritarchs, besides a variety of stromatolites. Presence of microstromatolites such as *Yelma* *digitata* suggest early Riphean age for Bagalkot Group, which is also supported by isotopic dating of Chitrabhaukot dolomite at 1600-1700 Ma. Badami Group also contains acritarchs and trace fossils that suggest Vendian age.

### Bhima Basin

The NE trending irregularly sinuous Bhima basin (Fig.5.22) consisting dominantly of limestone covers an area of 5200 km$^2$ and is situated to the northwest of Cuddapah basin and northeast of Kaladgi basin. It overlies the granitic basement of Eastern Dharwar craton with a profound unconformity and has faulted contacts at many places. Deccan Trap overlies Bhima basin in the north. The sediments have an aggregate thickness of about 270 m. The basin is well known for its large reserves of limestone and the newly discovered uranium occurrence near Gogi.

Pioneering work in the basin was done in the eighteen seventies by W. King and R. Bruce Foote, which was followed by the work of A.M. Heron and C. Mahadevan in 1949. The basin has been studied in recent years by N.V.B.S. Dutt in 1975 and S.M. Mathur in 1977. Janardhana Rao et al. (1975), Mishra et al. (1987) and Kale and Peshwa (1995) provide recent summary of the basin. The lithostratigraphy of the Bhima Group is given in Table 5.8.

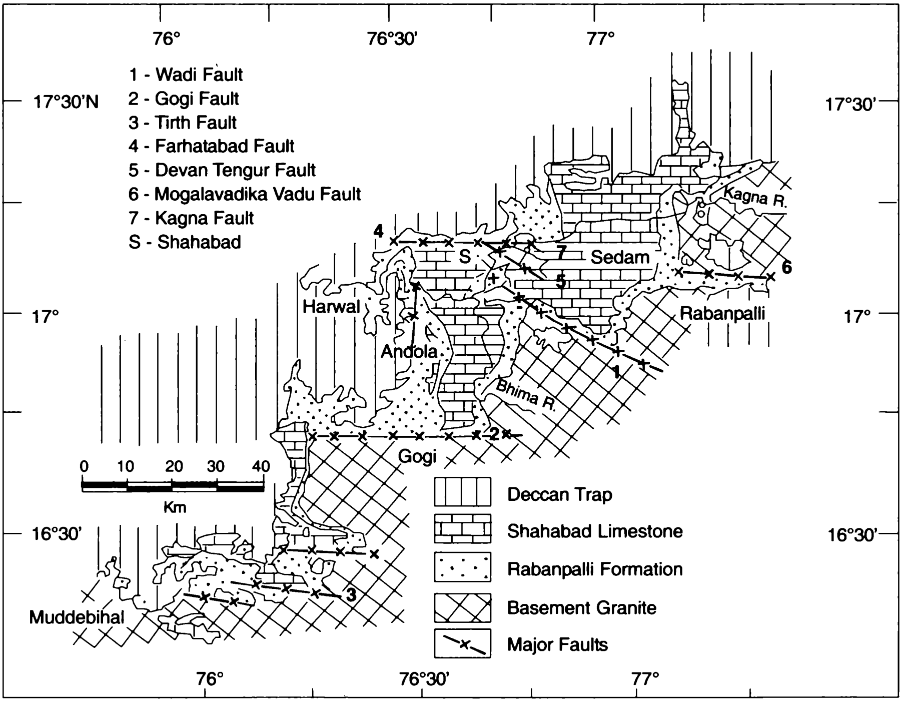
76°
76°30'
77°
17°30'N
17°30'
17°
17°
16°30'
16°30'
1 - Wadi Fault
2 - Gogi Fault
3 - Tirth Fault
4 - Farhatabad Fault
5 - Devan Tengur Fault
6 - Mogalavadika Vadu Fault
7 - Kagna Fault
S - Shahabad
Kagna R.
Sedam
Harwal
Rabanpalli
Andola
Bhima R.
Gogi
Muddebihal
0 10 20 30 40
Km
Deccan Trap
Shahabad Limestone
Rabanpalli Formation
Basement Granite
Major Faults
76°
76°30'
77°

**Fig.5.22.** Bhima basin in Dharwar craton (after Kale and Peshwa, 1991).

**Table 5.8.** Lithostratigraphy of the Bhima basin

| | | |
|---|---|---|
| Bhima Group | Andola Subgroup (30-70 m) | Harwal Shale (5 –10 m)<br>Katamdevarahalli Limestone (10-40 m)<br>Halkal Formation (15-20 m) |
| | | - - - - - - -Disconformity - - - - - - - - |
| | Sedam Subgroup (65-215 m) | Shahabad Limestone (45-130 m)<br>Rabanpalli Formation (20-85 m) |

## Description of Lithology

*Rabanpalli Formation* commences with conglomerate and 'grit' beds. The conglomerate consists of clasts of vein quartz, felspar and tourmaline set in a siliceous matrix and is exposed near Kachaknur and Muddebihal. Arkosic and quartz arenite, siltstone, laminated olive shale and well-exposed purple shale overlie the conglomerate horizon. *Shahabad Limestone* used in cement industry is flaggy, variegated and grey, with rare chert interbeds. These lithological units constitute the *Sedam Subgroup.* A break in sedimentation that ensued was represented by a disconformity marked by chert and limestone pebble conglomerate of *Halkal Formation* at the base of *Andola Subgroup.* The disconformable beds grade into orthoquartzite, and shale with barite. The shale graduates into *Katamdevarahalli Limestone* through a sequence of flagstones and siliceous limestones. The limestone is gradational with the overlying *Harwal Shale*, that marks the top of Andola Subgroup.

Bhima sediments are practically horizontal, but are disturbed along transverse faults, the most important one being near Gogi where it has cut across the Shahabad Limestone and basement granite, and is marked by limestone breccia and uranium mineralisation. Microbiota and palynofossils are compatible with the Neoproterozoic age of the Bhima Group.

## Correlation of the Purana basins of the Dharwar craton

A tentative correlation of lithostratigraphic units of different Purana basins of Dharwar craton is given below:

| | Cuddapah-Kurnool | Pranhita-Godavari | Kaladgi-Badami | Bhima |
|---|---|---|---|---|
| Kurnool Gp. | Kundair Sgp. | Sullavai/Usur Gp. | Badami Gp. | Andola Sgp. |
| | Jammalamadugu Sgp. | Penganga Gp | | Sedam Sgp. |
| Cuddapah Supergroup | Srisailam Quartzite | Albaka/Pamanuru Sst. | | |
| | Nallamalai Gp. | Mulug/Venkatapuram Gp. | Simikeri Sgp. | |
| | Chitravati Gp. | Mulug/Venkatapuram Gp. | | |
| | Papaghni Gp. | Mallampalli Gp. | Lokapur Sgp. | |

Gp. - Group; Sgp. - Subgroup, Sst. - Sandstone

## Igneous Intrusions in Purana Basins

Synsedimentary sills and flows of basic composition are seen at the basal portions of Bijawar, Gwalior, Abujhmar basins and the Papaghni sub-basin of Cuddapah basin. Felsic lavas and pyroclastics form part of the succession at different stratigraphic levels in Cuddapah, Vindhyan, Chhattisgarh, Khariar and Pranhita-Godavari basins. Dolerite dykes intrude the Purana basins in various horizons, but are not extensive. Granites occurring as domes within the basins are either regarded as intrusives or remobilised basement, as in the case of the eastern margin of the Cuddapah basin, and the Khaligarh granodiorite in Ampani basin. Syenitic bodies occur in proximity to the Purana basins especially near the boundary with the Eastern Ghats mobile belt and are described under EGMB (Chapter 4). Alkali syenites of Cuddapah basin are reported from Giddaluru, Idamakallu, Racherla and Gundlapalle, which are analogous to that of the "Prakasam Alkaline Province". Kimberlites *sensu lato* are by far the most important intrusions because of their rich potential for diamonds, and therefore are described below:

### Kimberlites

Most significant aspect of the igneous activity in the Purana basins is the emplacement of diamondiferous and non-diamondiferous kimberlite diatremes within and in close proximity to the basins within the cratonic basement (Fareeduddin and Rao, 2007). The Majhgawan and Hinota pipes in Panna area of Vindhyan basin (Chalapathi Rao, 2006)) and Wajrakarur and Chelima kimberlites associated with or in proximity to Cuddapah basin are already well known. New discoveries are prolific in the west of Cuddapah basin (Paul et al. 2006). Important new occurrences are also located within Indravati basin and around Khariar basin in Bastar craton. There is ongoing intensive search, which may bring to light new occurrences. The main period of emplacement of kimberlites and lamproites in Peninsular India is ~1000 Ma, although some younger ages are being reported

#### *Vindhyan Basin*

Majhgawan diatreme (Fig.5.23a) is a pear-shaped intrusion measuring 515 x 330 m at the surface, and its diameter reduces to 120 m at the depth of 300 m. It has intruded in the interval between Kaimur and Rewa Groups and is in contact with the Kaimur sandstone and Semri shale, and dips steeply inward at 70° (Fig.5.23b). Kimberlite contains abundant cognate and non-cognate xenoliths. Non-cognate xenoliths are a variety of Vindhyan sediments

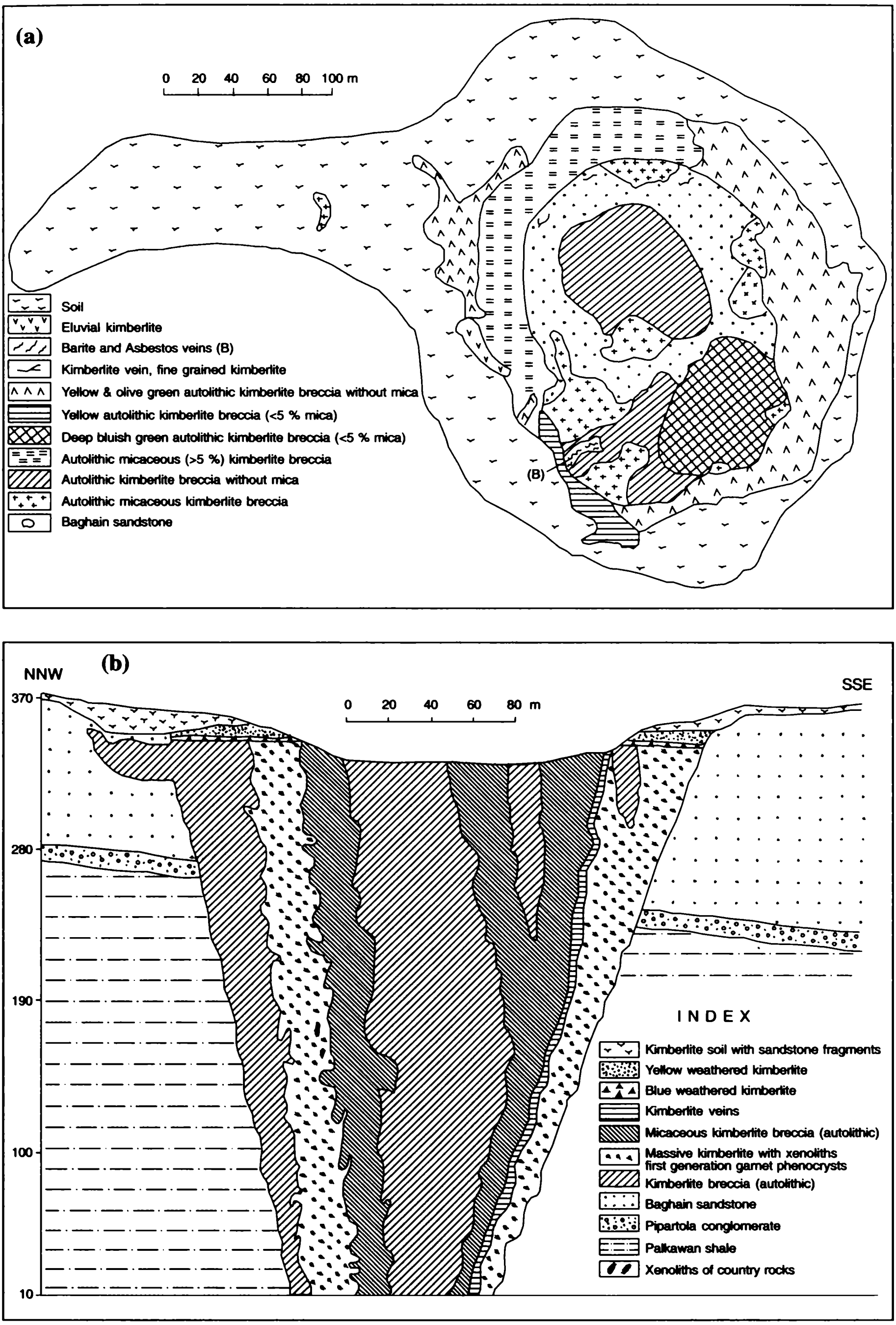
(a)
0 20 40 60 80 100 m
Soil
Eluvial kimberlite
Barite and Asbestos veins (B)
Kimberlite vein, fine grained kimberlite
Yellow & olive green autolithic kimberlite breccia without mica
Yellow autolithic kimberlite breccia (<5 % mica)
Deep bluish green autolithic kimberlite breccia (<5 % mica)
Autolithic micaceous (>5 %) kimberlite breccia
Autolithic kimberlite breccia without mica
Autolithic micaceous kimberlite breccia
Baghain sandstone
(B)
(b)
NNW
SSE
370
280
190
100
10
0 20 40 60 80 m
INDEX
Kimberlite soil with sandstone fragments
Yellow weathered kimberlite
Blue weathered kimberlite
Kimberlite veins
Micaceous kimberlite breccia (autolithic)
Massive kimberlite with xenoliths first generation garnet phenocrysts
Kimberlite breccia (autolithic)
Baghain sandstone
Pipartola conglomerate
Palkawan shale
Xenoliths of country rocks

**Fig.5.23.** (**a**) Geological map of Majhgawan kimberlite diatreme. (**b**) Cross section of Majhgawan kimberlite diatreme (after Soni et al. 2001).

and rare granite. This diatreme has now been classified as a lamproite containing olivine pseudomorphs, chrome-diopside, amphibole, phlogopite, chromite, garnet, magnetite, ilmenite, pervoskite, zircon, barytes, diamonds and a host of other minerals.

Hinota diatreme occurs close to Majhgawan diatreme and consists of basaltic and micaceous kimberlite grading into kimberlite breccia, and is broadly similar in composition to the Majhgawan body. The preferred Rb-Sr age of Majhgawan pipe is 1140±12 Ma and of the Hinota pipe is 1170 Ma.

### *Khariar Basin*

Five kimberlite rocks containing xenoliths of Khariar sediments named as Payalikhand I & II, Bahardih, Jangra and Kodomali have been recently discovered at the western margin of Khariar basin and belong to Mainpur kimberlite field. These are emplaced probably at the intersection of lineaments, between the Singhora and Chandarpur phases of sedimentation. The kimberlite diatremes are circular in plan with variable diameter of 50 to 300 m. Kodamali diatreme appears to be hypabyssal with groundmass of clinopyroxene and phlogopite. The other diatremes contain kimberlite breccia and tuff breccia. They consist of clasts of olivine, phlogopite, spinel, orthopyroxene, pyrope, picro-ilmenite and diamond in a dominant serpentine matrix. Three diatremes are diamond-bearing and more than 10% of the diamonds are >1 ct in weight.

### *Indravati Basin*

A circular ultramafic body of 2 km diameter from Tokapal that was earlier suspected to be a kimberlite (Ramakrishnan, 1987), has now been proved to be part of crater-facies kimberlite system. Three more pipes have been recently found at Duganpal, Bhejripadar and Parakot forming part of the Tokapal kimberlite field. Duganpal pipe is 300 m in diameter and consists of kimberlite with cognate and non-cognate xenoliths, breccia and tuff. The circular Bhejiripadar kimberlite consists of xenoliths of shale, sandstone and ultramafic nodules. Parakot weathered kimberlite consists of altered olivine and spinel.

### *Cuddapah Basin*

Nine kimberlite bodies have been found in a 100 x 30 km area from Kalyandrug to Jonnagiri in the Wajrakarur kimberlite field. These are located near Wajrakarur (pipe 1,2,6), Lattavaram (pipe 3,4,8,9), Muligiripalle (pipe 5) and Chigicherla (cc1 & cc2). Another cluster of kimberlites has been located in the Narayanpet kimberlite field (4 bodies near Maddur and one near

Kotakonda). The lamproite near Chelima intrudes the Cumbum Formation in Cuddapah basin. Pipe 1 of Wajrakarur field is the largest (1010 x 180 m) and the Kotakonda body is 1.5 km long and 50 to100 m wide. All the kimberlite diatremes are emplaced within the basement granitoids, except pipe 7 that intrudes the Ramagiri-Penakacherla schist belt in the form of a 500 m long dyke (Venkatampalle dyke). The Wajrakarur bodies are diatremes and Narayanpet bodies are of hypabyssal facies. Pipes 1 and 6 of Wajrakarur field are kimberlite breccias with crustal xenoliths. Pipes 3 and 4 are typical kimberlites and pipes 2 and 5 are lamproites. Narayanpet bodies are also kimberlites. Pipes 1,2,3,4,6,7 and cc-1 are diamond bearing. These kimberlites are dated at 1100 Ma, but some bodies have given older ages of 1350 Ma, which needs to be resolved by more detailed dating. The present view is that all the kimberlite bodies of India are probably contemporaneous at ~1000 Ma, although younger thermal impress (~500 Ma) is noted in some bodies.

## TECTONIC EVOLUTION OF PURANA BASINS

Purana basins occurring in a cratonic environment had a prolonged history of sedimentation punctuated by frequent breaks, from 1800 to 1000 Ma. Repetitive sequences of orthoquartzite-carbonate-pelite facies in numerous unconformity-bounded sequences suggest deposition is shallow water, most probably in the littoral zone or the coastal plain to shallow shelf. Turbidites and associated welded tuff, ignimbrite and felsic lava are probably formed in deep shelf, slope and basin. Local deep water environments marked by turbidites may suggest muddy shelves. Constant maintenance of shallow water environment throughout their sedimentation history despite the large thickness of 6 to 12 km suggests deposition keeping pace with sinking over a large time span. Shallow shelf sea or eperic sea environment is an appropriate model, although no modern analogues exist. One suggestion is an environment like the Rann of Kachchh. Palaeogeography of the Purana basins is shown in Fig.5.24 after Singh (1985).

These basins have developed on the craton contemporaneously with diastrophism in the intra- or peri-cratonic orogens like the Nellore schist belt (related to Papaghni sub-basin), Kotri-Dongargarh orogen (related to Abujhmar basin) and the Mahakoshal-Hindoli orogen (related to Bijawar and Gwalior basins). These intra-cratonic orogenies were succeeded by the amalgamation of cratons within the Southern Protocontinent consisting of Dharwar, Bastar, Bundelkhand and Singhbhum cratons in the period between 1800 and 2000 Ma. The initial stage of crustal stability was signified by the evolution of small basins with initial continental basaltic volcanism like the Bijawar, Gwalior and Abujhmar basins and Papaghni sub-basin during the brief incursion of the

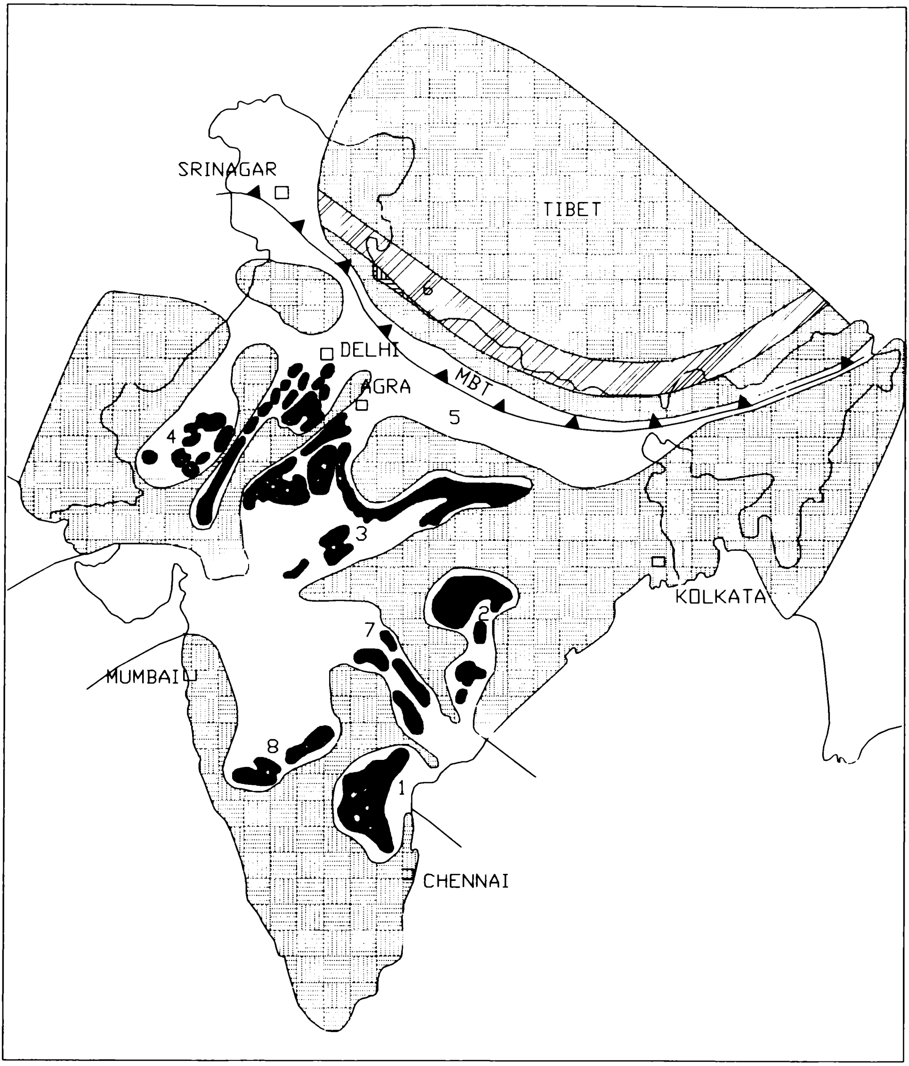

**Fig.5.24.** Palaeogeographic reconstruction of India during Meso-Neoproterozoic (ca. 600 – 1700 Ma). The unmetamorphosed sediments were laid down in an extensive shallow sea which existed in the form of embayments on the Indian subcontinent. The Vindhyan basin (3) was open towards west; in the north it may be connected to embayment of Gangetic Alluvium near Agra. It is also likely that in some parts of the sea, sedimentation started earlier than in the other parts and transgression-regression history in different basin show marked differences. **1** - Cuddapah basin, **2** - Chhattisgarh basin, **3** - Vindhyan basin, **4** - Marwar basin, **5** - Gangetic Alluvium-Lesser Himalaya embayment, **6** - Tethys zone, where sedimentation started in Neoproterozoic (ca. 700 Ma), **7** - P-G basin, **8** - Badami sub-basin. Black – Mesoproterozoic sediments on Peninsular India, white – sea, hatched-land, diagonal line – Tethys zone. MBT – Main Boundary Thrust denoting southern limit of the Himalaya (after Singh, 1985).

sea around 1800 Ma. Once the crust was fully stabilized, large basins were formed (e.g., Vindhyan, Cuddapah, Chhattisgarh, Bastar and Pranhita-Godavari basins). The Southern Protocontinent broke up later to produce continental margin orogens like EGMB (~1000 Ma) and Satpura (~1500 Ma) belts. This event was part of the worldwide orogenies at 1500 Ma and 1000 Ma. These continental-margin orogenies affected the adjacent 'Purana' basin margins with the formation of boundary thrusts, as in the case of Bastar, Chhattisgarh, Pranhita-Godavari and Vindhyan basins, and fold-thrust belts like the Nallamalai fold belt. The cratonic interior basins remained unaffected by orogeny as seen in the Kaladgi and Bhima basins. The sedimentation continued with a major hiatus until ~1000 Ma. Alkaline magmatism and carbonatite intrusions were confined to the continental rifts or fault systems like Dharmapuri 'rift zone' in the Dharwar craton. Thermal imprints of this extensional episode were felt in many Purana basins in the form of alkaline intrusions, after which they have become fully cratonised to form part of the present Indian shield. The evolution of these basins may be related to the development of supercontinental cycles. The Palaeoproterozoic (1600-1800 Ma) supercontinent dispersal and aggregation (Columbia supercontinent) was marked by the Mahakoshal-Hindoli orogen and Bijawar-Gwalior basin, as well as Cuddapah basin and Nellore schist belt. The Mesoproterozoic (1600-1000 Ma) supercontinental cycle (Rodinia supercontinent) was a major event in Peninsular India, seen in the development of the main Purana basins along with their interlinked mobile belts (Eastern Ghats). This probably corresponds to the global Grenville (1000-1100 Ma) event. The extensional regime after the Mesoproterozoic orogeny was marked by the emplacement of kimberlites (~1000 Ma). Some of these kimberlites were the source of diamonds in the basal conglomerates of 'Purana' basins like Kurnool, Chhattisgarh and Khariar. The Neoproterozoic (550-800 Ma) or Pan-African orogenic event of Pandyan mobile belt is followed by the emplacement of alkaline rock-carbonatite complexes of Dharmapuri and alkaline granites of Pandyan mobile belt. This event was regarded as penecontemporaneous with the evolution of Kurnool, Bhander, Sullavai and Badami Groups, but recent geochronology constrains the closure age of Purana basins to ~1000 Ma, and negates their Neoproterozoic (~500 Ma) correlation.

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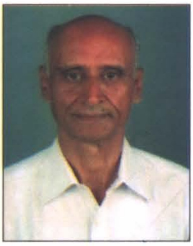

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